Dentistry 3000

Vol 14, No 2 (2026)
ISSN 2167-8677 (online)
DOI 10.5195/d3000/2026.1583

Performance of Milled versus Pressed Polyetheretherketone (PEEK) Frameworks for Removable Partial Dentures

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Abstract

Polyetheretherketone (PEEK) has gained increasing popularity as a metal-free framework material for removable partial dentures (RPDs). It can be processed through two principal routes — subtractive CAD/CAM milling from industrially pre-polymerized blanks, or analogue heat-pressing from granular raw material — yet the extent to which these fabrication techniques differentially affect framework performance remains a subject of ongoing investigation. To synthesize the available evidence comparing the mechanical, physical, biological, and clinical performance of milled versus pressed PEEK RPD frameworks, and to identify the fabrication route that best satisfies the demands of contemporary prosthodontic practice. A comprehensive narrative review was conducted across PubMed/MEDLINE, Scopus, Web of Science, and the Cochrane Library using Boolean search strings combining MeSH terms for polyetheretherketone, removable partial dentures, and fabrication techniques. Studies published in English between 2012 and 2026 were considered. Milled PEEK frameworks consistently demonstrated superior flexural strength (~158.7 MPa), tensile strength (~118 MPa), higher fracture resistance, lower surface roughness, and greater dimensional accuracy compared to pressed frameworks. Pressed PEEK can achieve clinically adequate retention when proper undercut depths (0.5–0.75 mm) and clasp dimensions are employed. Both routes produce biocompatible, non-cytotoxic frameworks; however, pressed frameworks show marginally higher microbial adhesion owing to surface irregularities and potential internal voids. CAD/CAM milling is currently the gold standard for fabricating PEEK RPD frameworks. Pressed PEEK represents a viable alternative for laboratories lacking milling infrastructure, provided stringent operator protocols are followed. Long-term randomized clinical trials are needed to confirm survival rates and standardize manufacturing criteria for both techniques.

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Citation: Al-Kanani KMA. (2026) Performance of Milled versus Pressed Polyetheretherketone (PEEK) Frameworks for Removable Partial Dentures. Dentistry 3000. 1:a001 doi:10.5195/d3000.2026.1583
Received: September 9, 2026
Accepted: September 19, 2026
Published: September 22, 2026
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Introduction

Partial edentulism remains a significant global health challenge. Despite widespread implant adoption, removable partial dentures (RPDs) continue as a vital, cost-effective treatment modality. For decades, cobalt-chromium (Co-Cr) alloys served as the standard framework material due to excellent mechanical properties and clinical longevity [1,2]. However, Co-Cr frameworks present notable shortcomings: visible metallic clasps compromise aesthetics; high density contributes to prosthesis weight; and the alloys carry risks of allergic sensitization, oral galvanism, and elevated plaque affinity [3,4].

In response, high-performance polymers (HPPs) have emerged as metal-free RPD framework alternatives. Among these, polyetheretherketone (PEEK) a semi-crystalline, aromatic thermoplastic of the polyaryletherketone (PAEK) family has attracted substantial research interest [5]. PEEK is distinguished by a bone-like elastic modulus of 3–4 GPa, excellent biocompatibility, chemical inertness, radiolucency, and low specific gravity (~1.3 g/cm³), making it biomechanically and aesthetically advantageous [6,7]. The key research domains surrounding PEEK RPD frameworks are summarized in Figure 1.

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The material is available in two principal forms for dental use: industrially pre-polymerized blanks or discs for subtractive CAD/CAM milling (e.g., breCAM BioHPP, JUVORA, Dentokeep), and granules or pellets for heat-pressing via analogue vacuum-pressing systems (e.g., the for2press system) [8,9]. A critical clinical question persists: does the choice of fabrication route materially affect the mechanical integrity, precision of fit, biological behavior, and clinical performance of the resulting RPD framework? The comparative fabrication workflows are illustrated in Figure 2.

Whereas CAD/CAM milling processes frameworks from blanks manufactured under standardized industrial conditions ensuring a porosity-free, homogeneous microstructure heat-pressing is highly operator-dependent, with variables such as preheating cycle accuracy, vacuum pressure, and manual divesting potentially introducing structural defects [10]. The aim of this narrative review is to synthesize the available evidence across mechanical, physical, biological, and clinical performance domains, with reference to the comparative data presented in Table 1.

Material and Methods

A comprehensive electronic literature search was conducted across PubMed/MEDLINE, Scopus, Web of Science (WoS), and the Cochrane Library. The primary Boolean search string was: ("polyetheretherketone" OR "PEEK") AND ("removable partial denture" OR "RPD") AND ("milled" OR "CAD/CAM" OR "pressed" OR "heat-pressed" OR "injection molding"). Publications in English between January 2012 and April 2026 were considered [11-13].

Inclusion criteria comprised original research articles (in vitro laboratory studies, in vivo clinical trials, and case reports), systematic reviews, and narrative reviews evaluating PEEK RPD frameworks fabricated by milling and/or pressing. Studies on fixed prostheses, implant-supported restorations, or non-dental PEEK were excluded. Study selection followed PRISMA: deduplication, independent abstract screening, full-text eligibility assessment, and consensus resolution [14].

Results

PEEK as a Dental Framework Material: Fundamentals

Chemical Structure and Grades

PEEK is an aromatic semi-crystalline thermoplastic whose backbone consists of repeating units of one ketone and two ether bonds, providing exceptional thermal stability (melting point ~343°C) and chemical resistance [15]. Unfilled PEEK represents the pure form with an elastic modulus closely approximating bone. Ceramic-filled PEEK (BioHPP; bredent GmbH, Senden, Germany) contains ~20% ceramic filler particles (0.3–0.5 µm) to enhance hardness and flexural strength [6]. Carbon fiber-reinforced PEEK raises the modulus to ~18 GPa, primarily for implant-supported frameworks [16].

Key Properties Relevant to RPD Frameworks

PEEK's elastic modulus (3–4 GPa) resembles bone and dentin, vastly lower than Co-Cr (~220 GPa). This flexibility reduces distal torque and stress on abutment teeth, though it necessitates greater clasp bulk (~1.5–2 mm) and deeper undercuts (0.5–0.75 mm) compared to metal clasps to achieve clinically acceptable retention [7,17]. Flexural strength ranges from 140–170 MPa across grades. PEEK demonstrates very low water sorption (<0.5%) and negligible solubility (<0.3 µg/mm³), and exhibits lower plaque affinity than metals or ceramics, supporting long-term periodontal health of abutment teeth [15,18].

Fabrication Techniques: A Detailed Comparison

The two principal PEEK fabrication routes are depicted in Figure 2. The key distinction lies in material homogeneity: milled blanks are industrially pre-pressed under standardized conditions (porosity-free), while pressed frameworks are fabricated from granules in a laboratory environment prone to operator-variable structural defects [10,19, 20].

Subtractive CAD/CAM Milling

As shown in Figure 2 (Workflow A), milling begins with a digital impression or master cast scan producing an STL file. The framework is designed in CAD software (e.g., 3Shape, exocad), surveyed digitally to determine path of insertion, and machined in a five-axis CNC milling unit from a pre-polymerized PEEK blank (BioHPP, JUVORA, Dentokeep) [21].

The finished framework requires minimal adjustment and benefits from diamond-paste polishing to achieve optimal surface finish [10,14]. Direct milling achieves trueness of ~17.36 µm, significantly superior to indirect pressed workflows [22].

Analogue Heat-Pressing

As depicted in Figure 2 (Workflow B), the pressing technique employs a lost-wax method analogous to conventional metal casting. A wax or resin pattern is invested in phosphate-bound refractory material. The muffle is preheated (630–850°C) to eliminate the pattern, cooled to ~400°C, and PEEK granules (BioHPP for2press) are injected under vacuum within ~35 minutes [8,21]. The critical limitation is operator dependency: variables including preheating cycle, vacuum calibration, and sandblasting during divesting can introduce internal porosities, reducing compressive strength by ~19% compared to milled PEEK [20].

Hybrid Digital-Pressed Workflows

A hybrid approach designs the framework digitally and mills or 3D-prints a resin pattern, which is then invested and pressed with PEEK granules. This reduces wax-up errors but retains the intrinsic limitations of the pressing process, including material contraction during cooling and mechanical inferiority relative to industrially pre-pressed blanks [10,20].

Summary of Previous Studies: Comparative Evidence

Table 1 summarizes the key studies comparing milled and pressed PEEK RPD frameworks across in vitro, in silico, and clinical study designs. The evidence base spans retention measurements, fit accuracy, fatigue resistance, and patient-reported outcomes, with the critical study by El Mekawy and Elgamal [21] providing the foundational in vitro retention data that is referenced throughout this review. Comparative Performance: Mechanical Properties

Flexural Strength and Modulus

As evidenced by multiple studies in Table 1, the fabrication route exerts a measurable influence on PEEK's mechanical behavior. Milled PEEK frameworks demonstrate flexural strength of ~158.7 MPa — 6% higher than injection-molded PEEK and 11% superior to FDM 3D-printed versions [20]. The flexural modulus for milled PEEK (3.9–5.5 GPa) exceeds pressed PEEK (~4.9 GPa), attributed to the homogeneous, porosity-free microstructure of industrially pre-pressed blanks [6].

Tensile and Compressive Strength

Milled PEEK demonstrates tensile strength of ~118 MPa compared to 91–97 MPa for pressed PEEK, and compressive strength of 147.9 MPa versus ~119.0 MPa for injection-molded equivalents [20]. The lower compressive resistance of pressed frameworks is consistently linked to internal microporosities that act as stress concentrators under occlusal loading a direct consequence of operator-variable pressing parameters.

Retention: The Effect of Fabrication on Clasp Performance

El Mekawy and Elgamal [21] the most cited study in this review, summarized in Table 1 demonstrated in a controlled in vitro study (20 maxillary Kennedy Class I BioHPP frameworks; 0.50 mm undercuts) that pressed frameworks provided significantly higher baseline retention (5.38 ± 0.20 N) than milled frameworks (3.40 ± 0.21 N; $p < 0.001$). Both groups showed a statistically significant progressive decline at 120, 720, and 1440 cycles corresponding to 1, 6, and 12 months of simulated clinical use ($p < 0.001$). At 1440 cycles, pressed frameworks retained 4.26 ± 0.40 N versus 2.55 ± 0.14 N for milled ($p = 0.004$), with both values remaining within the clinically acceptable range.

The systematic review by Al-Banyahyati et al. [12] identified fabrication technique, clasp dimensions, and aging protocols as the principal determinants of PEEK clasp retention. Micovic et al. and Mayinger et al. (both detailed in Table 1) confirmed that pressed and milled PEEK clasps provide clinically adequate retention, with CoCrMo exhibiting higher initial values [22]. Importantly, Mayinger et al. demonstrated that milled BioHPP® discs outperformed pressed PEEK after thermocycling, attributed to the superior industrial pre-pressing of the blank material [22]. Kakai [23] confirmed that PEEK frameworks of both types achieve retention within the recommended 2–10 N clinical range when design principles are appropriately applied [24].

<u>Fatigue Resistance and Fracture Load</u>

As shown in Table 1, Zheng et al. (cited within Al-Banyahyati's systematic review [12]) demonstrated that milled PEEK clasps survived 30,000 insertion/removal cycles with only a 6% fracture rate, compared to more frequent failures in cast and laser-sintered CoCr clasps. Milled PEEK FDPs show mean fracture loads of ~2,354 N versus ~1,738 N for granular-pressed equivalents [20], the difference driven by internal porosity in pressed frameworks. Wu et al. [33] confirmed stable retentive forces in PEEK clasps over fatigue cycling equivalent to five years of simulated function.

Comparative Performance: Physical and Surface Properties

<u>Surface Roughness and Polishing</u>

Milled PEEK typically exhibits lower initial surface roughness than pressed PEEK because industrial processing of the blanks produces a denser, more uniform material surface [11]. Pressed frameworks are more susceptible to surface irregularities from internal porosity and the sandblasting step during divesting. Both routes can achieve Ra < 0.13 µm optimal for minimizing Candida albicans and cariogenic Streptococci adhesion through laboratory polishing with diamond pastes [20]. Bächle et al. [25] confirmed that bacterial adhesion on PEEK is significantly influenced by manufacturing technique, with pressed frameworks exhibiting higher adhesion.

<u>Precision of Fit and Dimensional Accuracy</u>

As documented in Table 1, milled PEEK RPD frameworks achieve fit accuracy values of 43 ± 23 µm (horizontal) and 38 ± 21 µm (vertical), comparable to or better than cast Co-Cr [11,26]. Negm et al. [27] demonstrated that direct CAD/CAM milling yields significantly higher trueness (17.36 µm) than indirect heat-pressed frameworks (~71.68 µm), though both remained within clinical acceptability. Zhao et al. [28] confirmed reliable fit for milled PEEK frameworks in complex RPD geometries. Shaban et al. [29] found that both pressed and milled BioHPP produced clinically acceptable fit, with minor discrepancies in clasp geometry favoring milled specimens.[30]

Comparative Performance: Biological Properties

<u>Biocompatibility and Cytotoxicity</u>

PEEK is widely validated as biocompatible, nonmutagenic, and non-cytotoxic, with a chemically stable aromatic backbone that prevents release of toxic by-products [5,6]. It is ideal for patients with hypersensitivity to Co-Cr or nickel [31]. The biological equivalence of milled and pressed frameworks is established the polymer is chemically identical regardless of processing route, but pressed frameworks carry a marginally higher biological risk through surface irregularities facilitating microbial colonization [25].

<u>Plaque Affinity and Bondability</u>

PEEK demonstrates lower plaque affinity than zirconia and titanium, supporting periodontal health in abutment teeth [18]. Maintaining Ra < 0.13 µm via polishing is critical, particularly for pressed frameworks. Bonding to veneering composites requires mandatory surface modification: airborne-particle abrasion with Al_2O_3 followed by 98% sulfuric acid etching, and MMA-based primers achieving bond strengths exceeding 5 MPa (ISO 10477) [5,20].

Clinical Performance

<u>Retention and Patient Outcomes</u>

As summarized in Table 1, the clinical evidence for PEEK RPDs is characterized by high patient acceptance and favorable biomechanical responses. Ali et al. [32] in their pilot RCT crossover found both Co-Cr and PEEK RPDs significantly improved OHRQoL (OHIP-20); early scores favored PEEK, driven by improved aesthetics and comfort, with no significant functional difference. Zhai et al. [24] confirmed clinical equivalence between Bio-HPP and Vitallium frameworks in free-end RPDs over two years. Gomes et al. [34] reported excellent color stability, healthy periodontal responses, and absence of enamel wear on abutments at two-year follow-up in a non-metal RPD case series.

Clinically, PEEK clasps provide retentive values of 1.6–5.38 N, within the recommended range. To achieve optimal results, clasps should engage deeper undercuts (0.5–0.75 mm) and be designed with greater bulk (~1.5–2 mm thickness) to compensate for PEEK's lower stiffness compared to metal [7,12]. PEEK's low elastic modulus acts as a stress-breaker, reducing horizontal forces and distal torque on abutment teeth an advantage specifically beneficial in periodontally compromised patients [19,34].

Discussion

The evidence synthesized in Table 1, Figures 1 and 2, and the reviewed literature reveals a nuanced picture: milled PEEK frameworks generally exhibit superior mechanical properties and dimensional accuracy, while pressed PEEK can provide clinically adequate retention and fit when proper design parameters and meticulous laboratory protocols are observed.

The higher retention of pressed frameworks in in vitro studies [21,22] appears paradoxical given their documented mechanical inferiority. The explanation is that investment-and-pressing allows the material to flow conformally around the abutment geometry, creating close clasp-to-abutment adaptation and maximizing frictional contact [8,21]. Milling burs may introduce surface micro-irregularities on the internal clasp surface that reduce intimate adaptation [21]. After simulated aging, retention differences converge as both techniques exhibit progressive clasp deformation under cyclic insertion forces [12,22], a clinically important observation because it implies that long-term in vivo retention may be more similar between routes than in vitro baseline values suggest.

The predominance of internal porosity as the primary weakness of pressed PEEK deserves emphasis. Manual pressing errors reduce compressive strength by ~19% and fracture load by ~26% compared to milled equivalents [20]. Laboratories adopting pressed PEEK must invest in stringent process control. In contrast, milling's digital traceability and reproducibility are inherent quality-assurance advantages in contemporary workflows. As reflected in Figure 2, the pressing route involves substantially more operator-variable steps, each representing a potential source of framework compromise.

A critical methodological limitation of the existing literature is its heterogeneity, as highlighted by Al-Banyahyati et al. [12]: studies compare different PEEK grades (unfilled vs. BioHPP), different brands with distinct industrial processing histories, varying undercut depths, and inconsistent aging protocols. This explains the divergent retention trends across Table 1 and makes direct quantitative comparisons difficult. Standardization of testing methodologies is urgently required.

Conclusion

Based on the synthesized evidence (Table 1, Figures 1–2), the following conclusions are drawn:

1. CAD/CAM milling is the gold standard for PEEK RPD framework fabrication, providing superior flexural strength, fracture resistance, dimensional accuracy, and surface quality compared to analogue heat pressing.

2. Pressed PEEK frameworks exhibit higher initial clasp retention in vitro due to conformal adaptation but demonstrate lower mechanical

strength and greater susceptibility to internal porosity.
3. Both routes produce biocompatible, non-cytotoxic frameworks with low plaque affinity; pressed frameworks carry higher risk of surface irregularities that may compromise long-term biological performance.
4. Clinically, PEEK frameworks of both types when appropriately designed with 0.5–0.75 mm undercut depth and 1.5–2 mm clasp bulk provide satisfactory retention, excellent patient comfort, and favorable periodontal responses.
5. Long-term multicenter RCTs are necessary to establish definitive survival rates and standardize fabrication protocols for PEEK RPD frameworks.

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Vol 14, No 2 (2026) DOI 10.5195/d3000/2026.1583

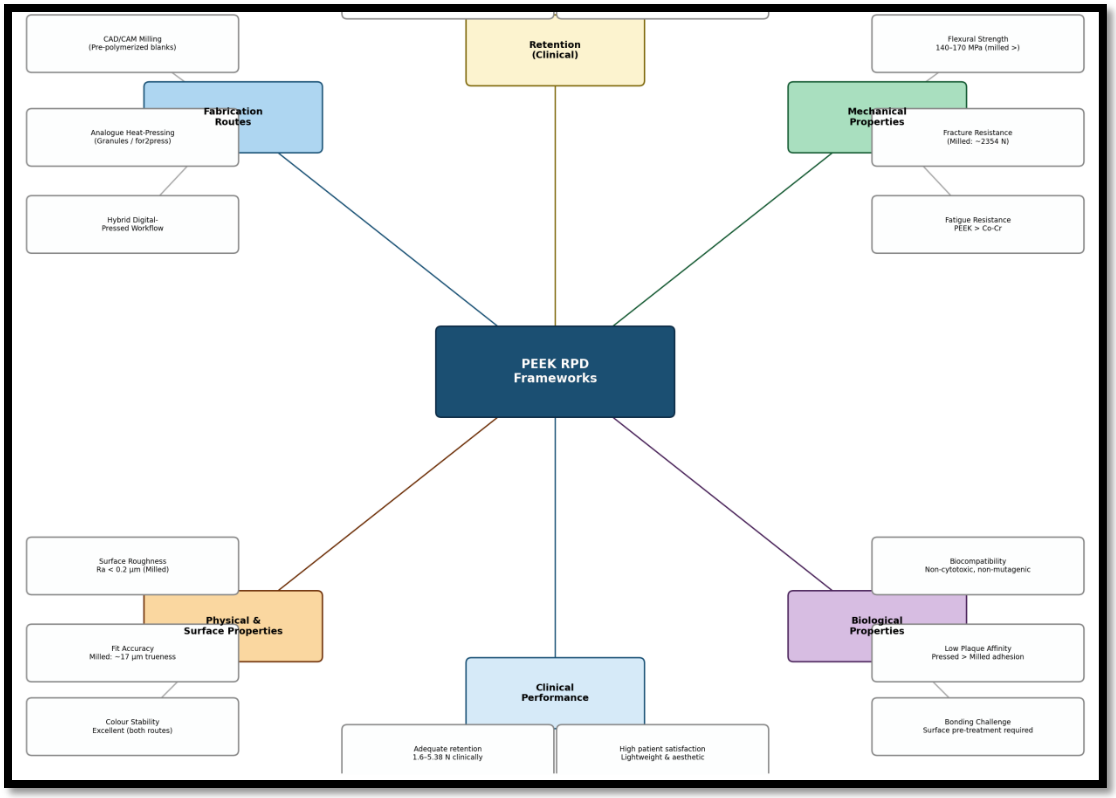

Figure 1. Map summarizing the principal research in PEEK removable partial denture framework performance. Six key areas (fabrication routes, mechanical properties, physical and surface properties, biological properties, retention, and clinical performance) radiate from the central theme, each subdivided into the primary evidence dimensions reviewed in this article.

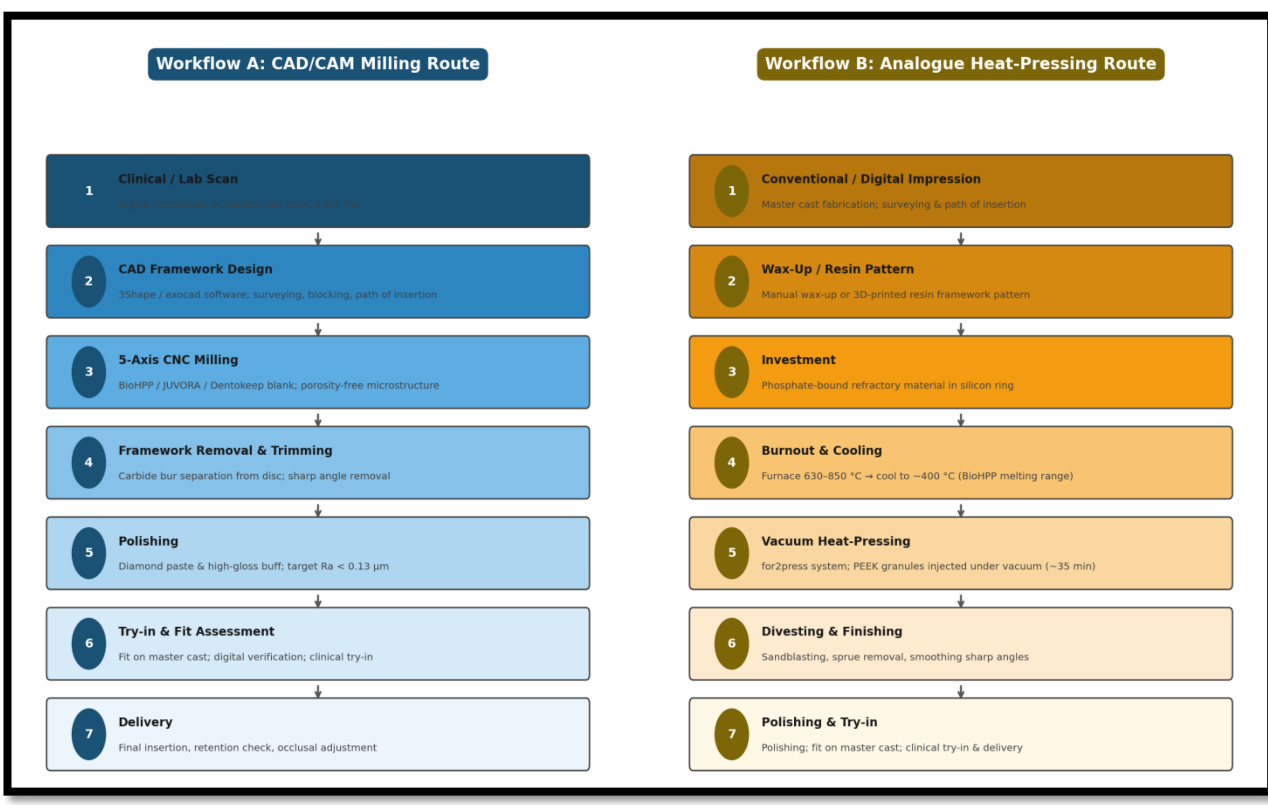

Figure 2. Representative step-by-step fabrication workflows for PEEK RPD frameworks. Workflow A (left, blue): CAD/CAM subtractive milling route from industrially pre-polymerized blanks from digital impression through five-axis milling, finishing, polishing, and try-in. Workflow B (right, amber):

Analogue heat-pressing route from master cast and wax pattern through investment, burnout, vacuum pressing (for2press system), divesting, and polishing.

Table 1. Summary of previous studies comparing milled versus pressed PEEK RPD frameworks (in vitro, clinical, and finite element analysis designs).

Author & Year	Study Design	Material / Groups	Key Outcomes	Conclusion / Implication
El Mekawy & Elgamal, 2021 [21]	In vitro	Pressed BioHPP (n=10) vs. Milled BioHPP (n=10); 0.50 mm undercut; 0–1440 cycles	Pressed: 5.38±0.20 N (baseline) → 4.26±0.40 N (1440 cycles). Milled: 3.40±0.21 N → 2.55±0.14 N. Both groups: significant decline over time (p<0.001)	Pressed PEEK provides significantly higher initial and sustained retention; milled PEEK remains within clinically acceptable range
Micovic et al., 2021 [22]	In vitro; artificial aging (180 days in artificial saliva)	Pressed BioHPP®; Milled Dentokeep; Milled BioHPP®; Cast CoCrMo (n=15 each); 50 cycles	CoCrMo exhibited highest initial retention (14.8 N). Pressed PEEK: −4.8 N start; relatively stable at 180 days. Between-brand milled differences significant at start; converged after aging	Retention varies by brand and aging; PEEK clasps remain clinically viable; pressed PEEK more stable over time vs. CoCrMo
Mayinger et al., 2021 [22]	In vitro; thermocycling + distilled water (60 days)	Pressed BioHPP®; Milled Dentokeep; Milled BioHPP®; Cast CoCrMo (n=15 each)	Milled BioHPP® showed 13.6 N increase at 60 days; Pressed PEEK declined 3.1 N. CoCrMo highest overall but declined significantly with aging	Milled BioHPP® discs show superior retention stability under thermocycling vs. pressed; brand-specific industrial pre-pressing key factor
Shaban et al., 2020 [29]	In vitro; fit evaluation	Pressed BioHPP vs. Milled BioHPP (Kennedy Class I mandibular); STL overlap analysis	Both techniques provided clinically acceptable fit. Minor discrepancies in clasp arm geometry favoured milled specimens	Milling achieves marginally superior dimensional accuracy; both routes are clinically suitable for mandibular RPDs
Negm et al., 2019 [27]	In vitro; 3D virtual fit analysis	Direct milled PEEK vs. indirect (3D-print-then-press) maxillary RPD frameworks	Direct milling trueness: 17.36 µm; indirect: 71.68 µm (p<0.001). Both within clinical acceptability	Direct CAD/CAM milling significantly superior in trueness; indirect workflows acceptable but less precise
Zhao et al., 2024 [28]	In vitro; digital trueness	CAD/CAM-milled PEEK RPD frameworks; STL overlap analysis of connectors, rests, clasps	Fit values for major connectors within clinically acceptable range; no statistically significant distortion in complex geometries	CAD/CAM milling yields reliable, reproducible framework suitability for complex RPD geometries
Tribst et al. (in Al-Banyahyati SR, 2025) [12]	In silico (FEA)	Akers' clasps: PEEK, polyamide, POM, gold, titanium, CoCr; 3 undercut depths (0.25, 0.5, 0.75 mm); 18 groups	PEEK retention: 6.45–18.36 N; CoCr: 21.78–65.37 N. PEEK exerted markedly less stress on periodontium than CoCr	PEEK clasps unsuitable at shallow undercuts due to low retention; adequate at 0.5–0.75 mm; superior stress protection vs. CoCr
Zheng et al. (in Al-Banyahyati SR, 2025) [12]	Fatigue simulation (30,000 cycles; SEM)	Dumbbell-shaped clasps: Milled PEEK (JUVORA), cast CoCr, laser-sintered CoCr (n=10 each)	Milled PEEK: significantly higher fatigue resistance than both CoCr groups (p<0.01); lower deflection resistance (p<0.001); fracture rate 6%	Milled PEEK clasps superior in cyclic fatigue over CoCr despite lower initial stiffness; SEM shows ductile fracture mode
Kakai, 2024 [23]	In vitro; retention measurement	Three RPD framework materials including PEEK; various designs	PEEK retention within clinically recommended 2–10 N range regardless of fabrication route	PEEK frameworks are viable across fabrication methods when

Author & Year	Study Design	Material / Groups	Key Outcomes	Conclusion / Implication
				appropriate design parameters are applied
Peng et al., 2020 [7]	FEA + fatigue test	VESTAKEEP® PEEK clasps vs. CoCr; taper ratios 0.5, 0.7, 0.9; 0.25 & 0.5 mm undercuts	Optimal taper ratio 0.5–0.9; PEEK clasps 2.06–3.67 N vs. CoCr 8.26 N; no significant long-term deformation difference (p=0.11)	Slender tapered PEEK clasps with 0.5 mm undercut provide sufficient retention with minimal abutment stress
Wu et al., 2023 [33]	In vitro; fatigue circulation	PEEK clasps: fatigue cycling simulating 5-year function; fit and retention measurements	Stable retentive forces maintained over simulated long-term use; no significant clasp adaptation loss	PEEK clasps retain function over extended simulated use; superior fatigue stability vs. metallic clasps
Ali et al., 2020 [32]	Pilot RCT crossover	Co-Cr vs. PEEK RPD frameworks in same patients; OHRQoL (OHIP-20) outcome	Both materials significantly improved OHRQoL; early scores favoured PEEK (aesthetics & comfort); no significant functional difference	PEEK RPDs clinically comparable to Co-Cr with improved patient-reported aesthetics and comfort
Zhai et al., 2025 [24]	Clinical (2-year follow-up)	Bio-HPP vs. Vitallium frameworks in free-end (Kennedy Class I/II) RPDs	Acceptable clinical stability and satisfaction in both groups; no significant difference in denture stability or abutment mobility	Bio-HPP (pressed) frameworks are clinically viable alternatives to Vitallium in free-end RPD applications
Gomes et al., 2024 [34]	Clinical case series (2-year follow-up)	Non-metal (PEEK) RPD frameworks; multiple patients	Excellent colour/texture stability; healthy periodontal responses; no enamel wear on abutments	PEEK RPDs demonstrate clinical longevity with superior biological outcomes compared to metal frameworks

Abbreviations: RPD = removable partial denture; FEA = finite element analysis; RCT = randomized controlled trial; SR = systematic review; PEEK = polyetheretherketone; CoCr = cobalt-chromium; BioHPP = high-performance PEEK (bredent GmbH); OHRQoL = oral health-related quality of life.