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Review

Balancing Mechanical and Hygienic Requirements in Removable Partial Denture Framework Design: A Narrative Review of Clinical, Finite Element, and Laboratory Evidence

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Abstract

Removable partial dentures remain a principal means of rehabilitating partial edentulism when fixed or implant-supported treatment is precluded by anatomical, medical, or economic factors. The rules governing the design of the metal framework were formulated largely through mechanical reasoning and clinical observation, well before the means existed to test them against outcomes, and have been transmitted for several decades with limited comparative validation. This narrative review examines the evidence underlying contemporary removable partial denture framework design across three streams of investigation that are rarely read together: longitudinal clinical studies, finite element analyses, and in vitro work. Successive sections address gingival coverage, finite element evidence on framework components, rest position, contralateral abutments and indirect retention, guide planes, direct retainers, framework materials and digital workflows, and survival, patient-reported outcomes, and implant-assisted designs. The association between coverage of the gingival tissues and gingival inflammation is the element best supported by clinical observation, although the experimental studies are small and short, and the longitudinal cohorts combined planned frameworks with intensive maintenance. Much of the remainder rests on computational or laboratory evidence, which is broadly consistent in direction but of unestablished clinical magnitude, and several values in routine use are conventions rather than derived thresholds. The evidence supports avoiding gingival coverage that the design does not require and treating maintenance as part of the design; it does not identify an optimal framework geometry, and comparative clinical evidence for most mechanical design choices is limited.

Keywords: removable partial denture; dental prosthesis design; dental clasps; finite element analysis; biomechanical phenomena; evidence-based dentistry

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1. Introduction

Partial loss of the natural dentition disturbs several functions of the masticatory system at once. The reduction in occlusal units impairs chewing efficiency and alters bolus formation and swallowing; loss of teeth in the anterior region affects articulation, and the accompanying loss of dental and alveolar support modifies lip and cheek contour, with consequences for appearance and for self-perception [1,2]. Global surveillance data quantify the endpoint of this process rather than its intermediate stages: complete tooth loss

is estimated to affect approximately 7% of adults aged 20 years and over, rising to about 23% among those aged 60 years and over [3,4]. Partial edentulism is considerably more common than these figures suggest, but it is reported far less consistently, since national surveys and burden-of-disease models generally record edentulism as a single category rather than by the extent and distribution of the residual dentition. Where the number, position, and periodontal status of the remaining teeth preclude a fixed restoration, and where insufficient bone volume, medical contraindications, or the cost of implant therapy exclude it, the removable partial denture (RPD) remains the principal means of rehabilitation, and the need for it persists rather than diminishes as populations retain more teeth into later life [5]. The metal framework is the structural element on which this treatment depends. Its function is not simply to carry artificial teeth, but to connect the components across the arch with sufficient rigidity that functional load is shared, in a controlled proportion, between the periodontal ligament of the abutment teeth and the mucosa overlying the residual ridge, two tissues whose mechanical behavior differs substantially.

The rules governing how that load should be distributed were formulated well before the means existed to assess them. The tradition associated with McCracken, which shaped teaching and laboratory practice throughout the second half of the twentieth century, resolved the problem in terms of support, stability, retention, and, above all, rigidity, favoring broad major connectors, multiple points of contact with the remaining dentition, and additional retentive elements wherever rotation of the prosthesis was anticipated [6]. These recommendations were internally coherent and mechanically plausible, derived from careful clinical observation, laboratory measurement of tooth displacement under simulated load [7], and from engineering reasoning applied to a lever system. What they were not derived from was a controlled comparison of design alternatives against clinical outcomes. For several decades, the conventions were transmitted essentially unchallenged, and where long-term recall data eventually became available, they did not always confirm the distinctions the conventions rested upon; clinical observations within an institutional recall system, covering three established retentive assemblies, disclosed no trend favoring any one of them [8]. The distinction that matters here is between mechanical plausibility and clinical demonstration. A design that is coherent as a mechanical account of load transfer may nevertheless be neutral or adverse in its effect on the tissues over years of service, and only outcome data can establish which.

Three developments have since made that gap visible. Finite element analysis now permits stress and displacement to be quantified within the abutment, the periodontal ligament, the mucosa, and the framework itself under loading conditions that could not be reproduced in patients for ethical and practical reasons, and it has been applied extensively to distal extension configurations, to rest position, and to framework materials [9,10]. Digital design and manufacturing workflows have reduced operator-dependent variability in the fabrication sequence and have introduced framework materials, principally the polyaryletherketones, whose mechanical behavior differs fundamentally from that of cast cobalt–chromium [5,11]. In parallel, longitudinal clinical and experimental studies have qualified assumptions that were previously treated as settled, reporting, in an experimental model, that coverage of the free gingival margin was followed by gingival inflammation without a detectable increase in plaque [12], and that a more tissue-covering connector design was associated with greater inflammation [13], while patients followed for ten and subsequently twenty-five years under intensive and repeatedly reinforced oral hygiene showed no significant periodontal deterioration [14,15]. It is from this body of work that a prophylactic school of framework design emerged, articulated most explicitly in the critical analysis by Owall and co-workers, which argued that design should be governed

first by the avoidance of tissue injury and plaque retention and only then by mechanical optimization [16].

These three streams of evidence (longitudinal clinical studies, finite element analyses, and in vitro investigations) address the same design decisions but are rarely read together. Clinical studies establish outcomes without identifying the mechanism responsible for them; finite element analyses identify mechanisms with a precision their modelling assumptions do not fully support; in vitro work characterizes components in isolation from the arch in which they function. Each stream is reviewed periodically within its own literature, and the resulting recommendations are correspondingly partial. This narrative review aims to examine the evidence underlying contemporary removable partial denture framework design across these three streams and to assess how far it supports giving hygienic requirements greater weight alongside mechanical ones. Throughout, the type of study supporting each claim is stated explicitly, so that the confidence in a given recommendation can be assessed from the evidence that generated it rather than from the frequency with which it is repeated. The practical purpose of the review is to indicate which design decisions currently rest on clinical evidence and which rest on mechanical reasoning alone, so that clinicians and dental technicians can weigh them accordingly.

2. Materials and Methods

This article was conceived as a critical narrative review. It does not claim to be an exhaustive, reproducible systematic review and was therefore neither registered nor reported according to PRISMA 2020. Reporting followed the principles of the Scale for the Assessment of Narrative Review Articles (SANRA) [17], with explicit attention to the justification of the topic, the formulation of aims, the presentation of the literature search, referencing, the indication of the level of evidence, and accurate data presentation.

The literature was identified through searches of MEDLINE (via PubMed) and Scopus, supplemented by backward and forward citation chasing of key articles; no journals were hand-searched. Search terms combined the concept of removable partial dentures with terms for framework design elements (occlusal rest, clasp, major and minor connector, guide plane, indirect retention), framework materials and fabrication methods (cobalt–chromium, polyaryletherketones, CAD/CAM, selective laser melting), and evaluation methods and outcomes (finite element analysis, von Mises stress, retentive force, framework fit, survival, patient-reported outcomes). No lower date limit was applied, and the earliest source retained dates from 1963. Only articles published in English were considered. The initial searches, last run in July 2026, were not logged. For transparency, the search was therefore repeated as eight thematic strings, one for each design question addressed in Sections 3–10, in PubMed on 15 November 2026 and in Scopus on 16 November 2026; the exact strings and the number of records returned by each are given in Table A1 (Appendix A). The repeated searches returned 1445 unique records in PubMed and 1846 in Scopus, about 2105 after removal of duplicates between the databases by title. Because the review argues for a change of emphasis, the titles of the records returned by the strings on gingival coverage, rest position, and indirect retention (279 unique records in PubMed and 219 further records found only in Scopus), and the abstracts where needed, were screened specifically for studies reporting results contrary to the principal claims. This identified a randomized clinical trial comparing two complete clasp assemblies [18,19], a laboratory study of indirect retention [20], three clinical comparisons of lingual bar and lingual plate connectors [21–23], and two reviews that question the assumed harm of distal torque and document the role of supportive care [24,25]; these are discussed in Sections 3, 5 and 6. No flow diagram is provided, because selection was purposive and is not presented as reproducible.

Article selection was purposive rather than exhaustive: priority was given to clinical studies with the longest follow-up, to finite element analyses reporting model validation and boundary conditions, and to in vitro studies with clearly defined protocols. Systematic reviews and meta-analyses were used as secondary sources where they summarized clinical or laboratory evidence that could not be examined study by study. Selection was made by the authors, without independent duplicate screening and without a formal procedure for resolving disagreements (Section 11.4). Where evidence was conflicting, both positions were presented. Given the heterogeneity of the included evidence, which spans clinical, laboratory, and computational studies, no formal risk-of-bias assessment or statistical pooling was undertaken; findings are synthesized narratively, and the level of evidence underlying each claim is indicated in the text. As a working rule, clinical studies were given more weight than computational or laboratory studies addressing the same question; observational clinical data were distinguished from randomized data; and computational studies were considered more informative where their boundary conditions, material models and validation status were reported. No formal grading system was applied, and this weighting reflects the judgement of the authors. The design, model parameters, validation status and main limitations of the principal studies are summarised in Table A2 (Appendix A). A study is listed in Table A2 when a numerical value or a design recommendation in the text depends on it. In this review, a finite element model is described as validated only when its output was compared with physical measurements, such as strain gauge or photoelastic data; reproduction of the boundary conditions of an earlier model, or agreement with the direction of published results, is not treated as validation.

3. Biomechanical Versus Hygienic Design Principles

3.1. Two Competing Sets of Requirements

The design of a removable partial denture (RPD) framework is governed by two sets of requirements that are complementary in aim but frequently conflict in practice [16]. Biomechanical requirements favour extension: broader major connectors, additional guide-plane contacts, and supplementary indirect retainers are generally held to improve the distribution of functional load and to resist prosthesis displacement. Prophylactic, or hygienic, requirements favour restraint, since every framework element in contact with hard or soft tissue creates a surface at which dental plaque may accumulate and from which inflammation may spread [1,16]. In practice they can rarely be maximised because the coverage that improves mechanical performance is also the coverage least well tolerated by the periodontal tissues (Table 1). Both serve the same aim: a prosthesis that functions and that the remaining tissues tolerate, so design is a matter of balance rather than of choosing one set over the other.

Traditional design, derived from the mechanistic tradition associated with McCracken [6], tended to resolve this tension in favour of support and rigidity. A prophylactic (hygienic) school, articulated most explicitly in the critical analysis by Owall and co-workers, argued instead that framework design should above all minimise the risk of tissue injury and plaque accumulation, in accordance with the principles of preventive dentistry [16]. The two approaches are better regarded as complementary than as opposed, since each addresses a genuine requirement of the prosthesis. The contemporary question is therefore not which school is correct in the abstract, but what the clinical evidence reveals about the biological cost of tissue coverage, a cost that remains relevant because RPDs continue to be a common treatment for partial edentulism despite the expansion of implant therapy [2].

Table 1. Differences in emphasis between traditional (mechanistic) and contemporary (hygienic) teaching on removable partial denture framework design, as characterised in the cited sources [6,16]; the columns do not describe mutually exclusive positions.

Design Parameter	Emphasis in Traditional (Mechanistic) Teaching	Emphasis in Contemporary (Hygienic) Teaching	Reported Effect on the Supporting Tissues
Relationship of the framework to the free gingival margin	Contact accepted where it improves support and stability	Clearance of approximately 3 mm maintained wherever anatomy permits ("open design"; a convention, see Section 3.3)	Coverage of the gingival margin is associated with gingival inflammation, which in one experimental model developed without a detectable increase in plaque [12,13,26]
Extent of major-connector tissue coverage	Broad coverage favoured for rigidity and load distribution	Coverage remained the least compatible with adequate rigidity	Greater coverage is associated with increased plaque retention and gingival inflammation [1,16]
Number of minor connectors and retentive elements	Multiple elements used to maximise retention and bracing	Reduced to the functional minimum	Fewer components simplify daily plaque control and maintenance [16]
Role attributed to maintenance	Described as secondary to the mechanical design [6,16]	Recognised as an important determinant of the long-term periodontal outcome	Under rigorous, repeatedly reinforced plaque control, no significant periodontal deterioration was recorded over 10–25 years [14,15]

3.2. Clinical Evidence for the Biological Cost of Coverage

A body of observational and experimental work has examined the periodontal consequences of RPD wear. Reviews of the field report a consistent association between RPD use and increased plaque retention, gingival inflammation, and caries risk on the remaining dentition [1]. In a survey of eighty-seven patients who had worn cobalt–chromium RPDs for five to six years, examined by a single calibrated examiner, mucosal lesions were uncommon, but a high prevalence of plaque, gingivitis, and gingival recession was recorded, concentrated on the tooth surfaces lying within approximately 3 mm of the denture components [26]. Associations between design features and the periodontal condition of abutment and non-abutment teeth have been reported in a cross-sectional clinical study of 205 patients [27].

More direct evidence comes from experimental gingivitis models, in which the confounding influence of general oral hygiene can be controlled. Orr and co-workers examined ten subjects wearing baseplates that positioned a connector in varying relationships to the gingival margin; a significant increase in gingival index developed where the appliance covered the gingival margin, and, notably, this occurred without a detectable increase in plaque, which suggests an effect of coverage that is not mediated solely by plaque retention [12]. A single-blind crossover experiment comparing a lingual plate with a cingulum bar reached a consistent conclusion: the more tissue-covering design was associated with greater gingival inflammation [13].

Later comparisons of the two mandibular connectors give a more qualified picture. In crossover studies of 14 and 15 patients, each wearing a lingual bar and a lingual plate for 8 weeks and 3 months, respectively, the plate was associated with greater probing depth [22] or a higher gingival index [23], although in the first of these the type of connector did not affect the subgingival levels of the periodontal pathogens measured [22].

In a 30-month comparison of 36 patients with distal-extension dentures under regular recall, plaque accumulation was greater with the lingual plate, but probing depth, gingival index and attachment loss did not differ between the connector designs, and periodontal conditions other than recession improved in both groups [21]. These studies are small and of short or intermediate duration, but they indicate that the effect of coverage is modified by maintenance and has not been shown to lead to attachment loss. A systematic review of biological complications in the moderately reduced dentition likewise found that pre-treatment and supportive care reduced complication rates, although gingival recession appeared to be favoured by a mandibular sublingual bar [25].

This evidence must, however, be read alongside the longitudinal studies of Bergman and colleagues, which qualify it in an important respect. In patients followed for 10 and subsequently 25 years, most of whom wore lower distal-extension dentures, carefully planned frameworks combined with intensive, repeatedly reinforced oral hygiene produced no significant deterioration of the periodontal status of the remaining teeth [14,15]. Because every patient in these cohorts received both a planned framework and intensive maintenance, the studies cannot separate the contribution of either factor: they show that periodontal deterioration was not inevitable under this combination, not that maintenance can compensate for any framework design or that the frameworks used were optimal. The cohorts were not designed to compare framework designs, so they qualify the experimental evidence without refuting it. Claims occasionally attached to this literature, for example, that narrow interproximal embrasures are specifically correlated with root caries or with attachment loss beyond a defined threshold, extend beyond what the cited primary reports demonstrate and are treated here with corresponding caution [28].

3.3. The 3 mm Clearance and Open Design

This evidence supports the widely stated design convention that framework components should be kept clear of the free gingival margin. The clearance recommended depends on the component and the arch. For the mandibular lingual bar, a distance of at least 3 mm between the superior border of the bar and the gingival margins has been described as essential, together with a bar height of at least 4 mm, so that the connector needs about 7 mm between the gingival margins and the functional floor of the mouth [29]; teaching texts give 3–4 mm for mandibular major connectors and at least 6 mm for the borders of maxillary major connectors [30]. A figure of 3 mm is also used for bar clasps, but it describes a different distance: the horizontal part of the approach arm is kept about 3 mm apical to the gingival margin, in the buccal vestibule, before the arm turns to cross the margin, so the figure depends on vestibular depth rather than on the position of a connector border [31] (Section 8.2). No equivalent figure was identified for minor connectors or denture-based margins, which necessarily approach or cross the gingival tissues. The experimental observation that coverage of the gingival margin provokes inflammation independently of plaque provides a plausible rationale for this "open design" [12]. Where anatomy renders contact unavoidable, most commonly where insufficient vertical space precludes a lingual bar and a lingual plate must be used, relief is provided on the working cast so that the framework does not exert ischemic pressure on the mucosa, and the number of minor connectors is kept to the functional minimum.

It should be emphasized, nonetheless, that these figures are long-standing clinical conventions rather than experimentally derived optima. No comparative study has established any of them as a threshold by contrasting graded clearances, and the observation that plaque, gingivitis, and recession were concentrated within about 3 mm of the denture components [26] describes where lesions were found rather than a safe distance. Presented

as component-specific conventions supported by, though not derived from, controlled evidence, the principle is defensible without implying a universal clearance threshold [28].

3.4. Critical Synthesis

Taken together, the evidence supports avoiding gingival coverage that the design does not require, tempered by the recognition that the standard of maintenance is itself an important variable [14,15,21]. It does not show that any particular framework geometry is clinically optimal. What this literature establishes is an association between framework proximity and gingival inflammation, reinforced by experimental models; what it does not establish is the precise magnitude of the effect, nor the relative contribution of individual framework components under function. To move from association towards a quantitative account of how specific design choices load the supporting tissues, the field has turned to finite element analysis, considered in the following section.

4. Finite Element Evidence on Framework Components

4.1. The Contribution and the Limits of Finite Element Analysis

Finite element analysis (FEA) has become the principal computational tool for quantifying the mechanical behavior of removable partial denture (RPD) frameworks, allowing the simulation of stress, strain, and deformation under loading conditions that would be difficult or unethical to reproduce in a clinical trial. A typical analysis proceeds through the import of anatomical geometry, meshing, assignment of material properties, definition of boundary conditions and loads, and post-processing of the resulting stress and displacement fields [9]; the same computational framework has been applied across prosthodontics more widely, from treatment planning to material selection [32]. What the method yields, however, is only as dependable as the assumptions built into it. The complexity of the model and the fidelity with which mandibular kinematics are represented materially affect the results obtained [33], and the great majority of published simulations still assume static loading and homogeneous, linearly elastic materials, whereas masticatory function is dynamic, cyclic, and multidirectional [9]. FEA is therefore best understood as a tool that identifies where and under what conditions stress concentrates within a given design; it does not, on its own, establish that such a concentration is clinically consequential.

4.2. Distal-Extension Dynamics: Differential Compliance and the Fulcrum Line

The Kennedy Class I and II distal-extension configuration, in which the denture base on one or both sides lacks a posterior abutment tooth, presents the most demanding biomechanical scenario in RPD design, because it combines two supporting tissues of quite different compliance within a single rigid framework. The abutment tooth is restrained by the periodontal ligament (PDL) and the alveolar bone, a relationship commonly approximated in finite element models by fixing the outer surface of the periodontal ligament [34]. The free-end mucosa, by contrast, is substantially more compliant and exhibits viscoelastic behavior. Under occlusal loading, the terminal abutment may be regarded as a cantilever, and this compliance mismatch is modelled as producing asynchronous deformation between the tooth-borne and tissue-borne portions of the denture base. The resulting stress imbalance is transmitted through the rigid framework as distal torque on the terminal abutment: finite element studies typically locate peak stress in the apical and distal regions of the abutment root, a pattern compatible with distal tipping and, over time, disruption of the proximal contact with the adjacent tooth, although the latter has not been demonstrated clinically [9].

This behavior is classically summarized as rotation about a fulcrum line (Figure 1): an axis running through the terminal abutments (in a Kennedy Class II arch, diagonally between the abutment adjacent to the extension base and the most posterior abutment on

the opposite side), about which the denture base is considered to rotate as it moves toward or away from the supporting tissues. The position of this axis is not fixed by anatomy alone; it is generally held to depend on where the occlusal rest is placed relative to the terminal abutment, a relationship examined further in Section 5 [7]. Later finite-element comparisons of distal-extension designs indicate that, although the underlying compliance mismatch is common to every case, the magnitude of the resulting rotation and the stress transmitted to the abutment, PDL, and mucosa vary with the retentive and connector designs employed [35,36]. The fulcrum-line description, like the lever analogies used in Section 5, is a simplified two-dimensional model of a three-dimensional system, in which the axis of rotation changes with the direction and point of application of the load. The selection of a contralateral abutment in Kennedy Class II arches further modifies this rotational behavior and is examined in Section 6.

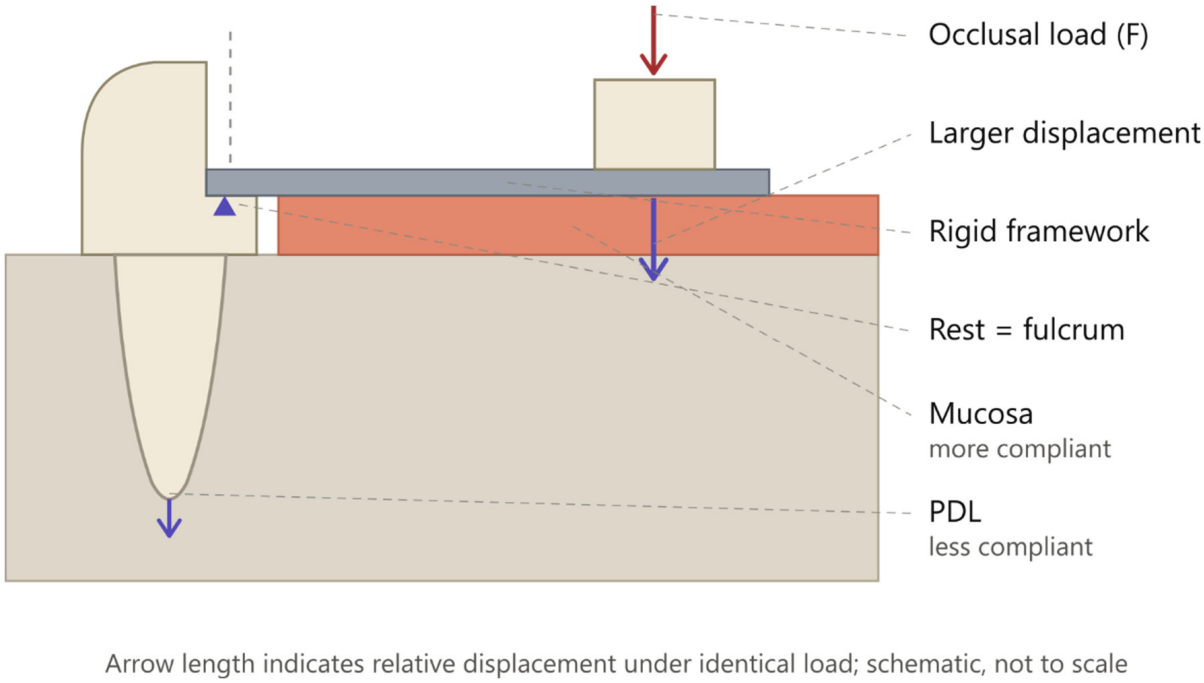


Figure 1. Schematic sagittal cross-section of a distal-extension removable partial denture. The abutment tooth is restrained by the periodontal ligament (PDL) and moves little under load, whereas the denture-bearing mucosa is more compliant and permits larger displacement of the extension base; the rest acts as the fulcrum of the rigid framework. Arrow length indicates relative displacement under an identical load. The diagram is schematic and not to scale.

4.3. Tissue Modelling: Viscoelastic Mucosa and the Linear-Elastic Simplification of the Periodontal Ligament

The two supporting tissues are not only mechanically dissimilar but are also modelled with different degrees of fidelity. The viscoelastic compliance of the denture-bearing mucosa has been represented explicitly in at least one RPD model, in which a viscoelastic denture adhesive layer between the denture base and the oral mucosa was approximated using a Prony series, allowing the model to reproduce the compliance of the soft-tissue interface under simulated bite forces rather than treating it as a fixed, unyielding boundary [37]. The PDL poses a different problem. Anatomically, it is a non-homogeneous, anisotropic tissue that does not behave in a linearly elastic fashion; for computational tractability, however, the vast majority of RPD finite element studies model it as a homogeneous, isotropic, linearly elastic material [9]. Comparative work that has varied the boundary conditions and failure criteria applied to the periodontal ligament indicates that this simplification is not neutral:

the stress values obtained are sensitive to which assumptions are adopted [38,39]. Models that instead incorporate non-linear, load-dependent material behaviour for the periodontal ligament and mucosa remain uncommon in the RPD literature [40]. Cast cobalt–chromium is usually assigned isotropic, linearly elastic properties, a simplification that is probably less consequential than for the biological tissues, although this has not been tested formally in the studies reviewed here.

4.4. Recurring Findings: Stress Concentration and the Minor-Connector Junction

Despite differences in Kennedy classification, framework material, and retainer design, finite element studies of RPD frameworks converge on a small number of recurring stress-concentration sites. A review of FEA-based RPD studies found that stress in free-end saddle designs concentrates chiefly at the clasp shoulder, at the horizontal curvature of the gingivally approaching clasp arm, and in the portion of the major connector adjacent to the terminal abutment, with a comparable concentration at the junction between the retentive arm and the minor connector [10]. At the rest itself, stress is consistently reported to peak at the junction between the rest seat and the minor connector, and a right-angled transition between the two has been reported to reduce this concentration relative to alternative geometries [9]. Studies reporting von Mises stress separately for the abutment, PDL, mucosa, and framework confirm that this concentration is compartmentalised rather than diffuse, with each structure carrying a distinct, geometry-dependent stress signature under an identical occlusal load [36]. The consistency of these findings across otherwise heterogeneous study designs is among the more robust contributions FEA has made to RPD framework design, even though, as discussed above, the absolute values obtained remain sensitive to the modelling assumptions on which they rest.

5. Occlusal Rest Position and Lever Mechanics

5.1. Conventional Practice: The Distally Placed Rest

As introduced in Section 4.2, the fulcrum about which a distal-extension prosthesis rotates is not fixed by anatomy alone but is generally considered to depend on the position of the occlusal rest on the terminal abutment [7]. For most of the twentieth century, however, this relationship was not the primary consideration governing rest placement. The conventional position, consistent with the broader mechanistic tradition described in Section 3 [6], was the distal marginal ridge of the abutment, immediately adjacent to the edentulous extension area: locating the rest as close as possible to the base it supported was considered the most direct mechanical solution, intended to minimise the effective length of the extension saddle and to transfer its load along the shortest available path. This convention remained standard teaching for several decades before its consequences for the abutment tooth itself were directly examined. Because the movement of an abutment tooth under a functioning prosthesis cannot be observed directly in the mouth, the assumption that rest position was mechanically neutral to the tooth went largely untested until it was subjected to controlled laboratory measurement.

5.2. The Distal Rest and the Fulcrum Effect: A Lever Arrangement Considered Unfavourable

When the rest is placed distally, it also functions as the effective fulcrum about which the rigid framework rotates whenever the extension base is loaded and displaces into the underlying, more compliant mucosa. This arrangement is occasionally described, in classic clinical teaching, as behaving like a pump handle: because the retentive clasp terminal is seated in an undercut and cannot simply disengage as the framework attempts to rotate about a fulcrum so close to it, the rotational tendency is instead transmitted directly into the abutment tooth as a torquing moment, an arrangement loosely equivalent, in a simplified

model, to a first-class lever, with the fulcrum interposed between the load applied at the extension base and the resistance offered by the tooth.

The principal direct evidence on this point remains Kratochvil's laboratory comparison of abutment tooth movement under different rest positions. Using an instrumented mandibular model under a simulated distal-extension load, this classic investigation found that a distally placed rest produced a posterior tipping tendency at the abutment, a direction of movement carried toward the edentulous space, where no adjacent tooth exists to share or resist the resulting force [7]. The same investigation reported that the gingival tissue immediately posterior to the abutment was more liable to be pinched between the rest and the tooth surface when the rest was placed distally, and that a rigid retentive arm engaging the distal curvature of the tooth could exert a further torquing effect as the denture base moved under function [7]. Taken together, this laboratory evidence suggests that a distally placed rest is associated with a tipping tendency directed toward unsupported tissue. A single loading cycle of this kind is unlikely to be consequential in isolation; the concern raised by this body of work is cumulative, in that mastication subjects the abutment to many thousands of such cycles over the working life of the prosthesis. A tipping tendency directed toward unsupported tissue is, in principle, less easily accommodated over time than one directed toward a tooth that can share the load. However, this has not been shown clinically.

5.3. The Mesial Rest: Redirection Toward a Supported Axis

Repositioning the rest mesially shifts the effective fulcrum away from the extension base and toward the remaining dentition. Kratochvil's comparison found that this reversed the direction of the tipping tendency described above: rather than tipping posteriorly into unsupported space, the abutment tended to tip anteriorly, a direction in which the proximal contact of the adjacent tooth reinforces it. The same study reported that a mesially placed rest directed the load transmitted through the mucosa-borne portion of the denture along a path closer to perpendicular to the residual ridge and reduced the likelihood of the posterior gingival tissue being pinched between framework and tooth, relative to a distal rest [7].

This repositioning also alters the behavior of the retentive arm. With the fulcrum moved mesially, a retentive component approaching the tooth from a more gingival or distal direction is not forced further into its undercut as the extension base settles under load; it is instead free to move fractionally away from the tooth, reducing the force transmitted to the abutment as the base displaces. This behavior is loosely analogous to a second-class lever and is the mechanical basis of what the literature terms a stress-breaking clasp design, considered further in Section 8. Release of the retentive terminal is not a property of the rest position alone: it depends on the geometry of the whole assembly formed by the abutment, the proximal plate and the retentive arm, including the position of the rigid part of the arm relative to the survey line. The overall effect is to redirect functional load closer to the long axis of the abutment tooth, the orientation in which the periodontal ligament is best able to accommodate it [7]. On the strength of this comparison, a mesially placed rest, combined with a retentive arm capable of moving fractionally with the settling denture base, became the preferred convention for the terminal abutment of a distal-extension prosthesis wherever the anatomy of the tooth and its survey line permitted it (Figure 2). The specific clasp assemblies built around this principle are considered in Section 8.

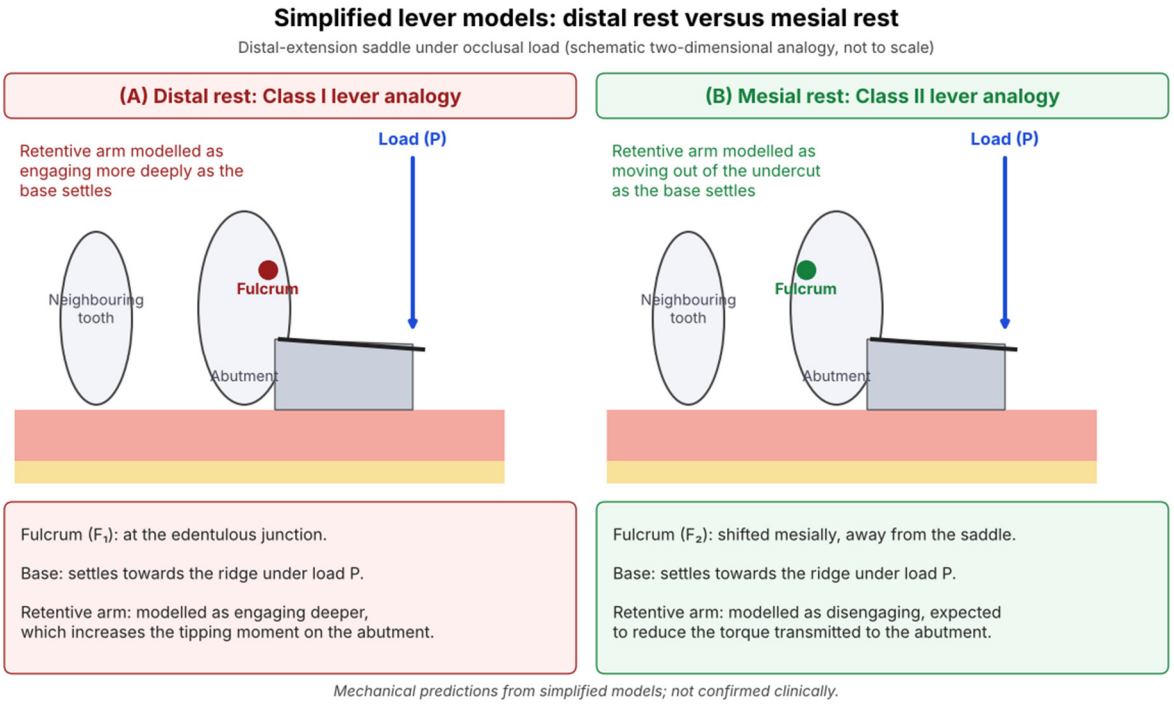


Figure 2. Biomechanical comparison of lever mechanics under occlusal loading for distal extension removable partial dentures (RPDs). (**A**) Distal rest: the fulcrum (F_1) lies at the edentulous junction, and the retentive arm is modelled as engaging more deeply into the undercut as the base settles, which increases the tipping moment on the abutment. (**B**) Mesial rest: the fulcrum (F_2) is shifted mesially, and the retentive arm is modelled as moving out of the undercut, which is expected to reduce the torque transmitted to the abutment. Both panels are simplified two-dimensional models; the lever classes are analogies, and the effects shown are mechanical predictions not yet confirmed clinically.

5.4. The Evidentiary Basis: Mechanical Reasoning Versus Direct Clinical Comparison

The evidence underlying this section is predominantly mechanical. Kratochvil's comparison was a laboratory measurement of tooth displacement in which rest position and clasp design were varied together [7], so its results describe complete assemblies rather than the rest in isolation, and subsequent support has come chiefly from finite element models. A three-dimensional finite element analysis of a two-premolar model, loaded by displacing a mesial or a distal rest 0.05 mm apically, reported a measurable difference in abutment displacement and periodontal ligament stress between the two rest positions; the largest values (a distal displacement of 42 µm at the buccal cusp and a principal compressive stress of 0.35 MPa in the ligament) occurred with a distal rest free to move horizontally, but a single vertical load from either position remained within the physiological tolerance of the supporting tissues [34]. A further finite element study, of an isolated mandibular second premolar abutment, compared a mesial rest alone with mesial and distal rests together under a 26 N bilateral load and favoured the use of both rests [41], which indicates that the results depend on the rest configuration modelled and cannot be generalised from one design to another. An earlier review found that the literature then available substantiated neither the assumption that distal torque from a rotating extension base harms the abutment nor the benefit of constructions designed to reduce it, and that periodontal treatment before insertion and regular recall were associated with a favourable prognosis [24]. In vivo, measurements in a single subject showed that the force on a premolar abutment was directed most posteriorly with a distal rest alone and most anteriorly with a mesial rest alone [42], in agreement with the laboratory findings. The only randomised clinical comparison identified did not test rest position in isolation: 134 patients with Kennedy Class I or II arches received

either mesial rests with I-bar retainers or distal rests with cast circumferential clasps, and after five years the success rates (76.6% and 71.3%) and nine periodontal measures of the abutment teeth did not differ significantly [18], while masticatory performance became similar in the two groups [19]. The directional preference for a mesial rest is therefore consistent across laboratory, computational and in vivo force measurements, but the one randomised comparison of complete assemblies built on the two rest positions found no clinical difference. A rest position cannot be evaluated independently of the clasp assembly, the guide planes, the support of the extension base and the load applied, and the recommendation is best read as conditional on those features.

6. Contralateral Abutments and Indirect Retention

6.1. Cross-Arch Support and the Problem of Abutment Selection

In Kennedy Class II arches, the terminal abutment on the extension side cannot by itself resist the rotational tendency described in Section 4; stability under function depends substantially on the tooth selected as the secondary abutment on the opposite, dentate side of the arch, a relationship generally described as cross-arch support. A finite element study of a maxillary Kennedy Class II framework, summarised in a recent review [9], placed the occlusal rest of the contralateral clasp assembly on the canine, the first premolar, the second premolar or the first molar; the rests were restrained rather than supported by a modelled periodontal ligament, and a vertical or buccally oblique load of 60 N was applied to the extension base [9,43]. With the rest on the canine or the first premolar, the framework was less resistant to the oblique load, and the second premolar gave the smallest saddle displacement; mucosal stress was insensitive to the abutment chosen, and the differences under vertical load were small [43]. A plausible mechanical explanation is the inclined lingual or palatal surface of the canine crown, which offers less resistance than a premolar or molar rest seat to a component displaced across it under oblique load; this explanation was not tested in the model. The model cannot establish clinical outcomes, and no clinical study was identified that compared a canine with a posterior tooth as the contralateral abutment in terms of abutment survival, mucosal complications, or patient satisfaction. The clinical data identified on abutment type do not indicate a poorer prognosis for canines: in a retrospective cohort of 172 RPDs followed for a mean of 44.9 months, the hazard of abutment loss relative to incisors was 0.196 for canines and 0.449 for premolars [44], although that analysis did not distinguish contralateral from primary abutments.

On these grounds, a premolar or molar rather than a canine is generally suggested as the contralateral abutment where the dentition allows a choice [9]; in the model described, the second premolar performed best, and the first molar did not perform better than the second premolar [9,43]. It should be noted, however, that this evidence derives from a single static finite element model of one maxillary arch with one clasp assembly and restrained rests, not from clinical comparison; the result has not been tested in other geometries, and its clinical magnitude, expressed for example as a difference in abutment survival, has not been established.

6.2. Indirect Retention: A Persistent Controversy

Whether indirect retainers achieve their stated purpose is one of the more unsettled questions in RPD design, and it has been unsettled for long enough that reviews of the topic routinely open by noting the absence of consensus rather than by describing one [45]. The theoretical justification is straightforward: positioned at a distance from the extension base, an indirect retainer is meant to function as a secondary fulcrum that resists rotational displacement of the denture base and reduces the leverage transmitted to the primary,

direct-retaining abutment. Direct experimental evidence for this mechanism, however, is limited, and what exists complicates rather than confirms the simple picture.

The earliest controlled laboratory test of the mechanism lifted a mandibular bilateral distal-extension framework from a model under standardised conditions while the clasp type, the location of the indirect retainer and the position of the rest seat on the terminal abutment were changed in turn. The indirect retainer was of limited use in preventing occlusal displacement of the denture base; the type of clasp had the greatest influence on base movement, proximal guide planes also helped to prevent lifting, and mesial rests did not reduce indirect retention compared with distal rests [20].

An in vitro study using electronic speckle pattern interferometry (ESPI), a high-resolution, non-contact technique capable of resolving tooth displacement under load, compared a Kennedy Class I mandibular framework with and without an indirect retainer, applying tensile loads of 0.15 to 0.70 N, perpendicular to the ridge (that is, loads tending to lift the base away from the ridge), to the longest free-end saddle of an acrylic master model without periodontal ligament simulation. Two findings are relevant here. First, the abutment teeth on the side contralateral to the loaded extension showed greater deformation when the indirect retainer was present than when it was absent, a result consistent with the retainer distributing stress more broadly across the arch rather than concentrating it on the primary abutment alone. Second, the behaviour of the abutment adjacent to the loaded extension itself depended on the intensity of the applied force: at low loads, the indirect retainer was associated with reduced deformation of this abutment, but at higher loads, deformation increased relative to the model without a retainer. The authors interpreted this reversal as indicating that the protective effect of the indirect retainer is limited and depends on the intensity of the force. On this evidence, the authors concluded that indirect retention aids the distribution of tensile force across the remaining dentition but questioned whether it reliably protects the primary abutment against excessive torque, and they explicitly called for further validation using complementary methods, including in silico and ex vivo approaches [45].

Three outcomes need to be distinguished here: resistance to separation of the denture base from the ridge, which is what both laboratory studies measured [20,45]; loading of the abutment teeth, which the ESPI study inferred from deformation under very low tensile loads in a model without a periodontal ligament [45]; and patient satisfaction, which was examined in a separate cohort (Section 10.2) [46] and does not test whether an indirect retainer prevents lifting or protects the abutments. This finding does not stand in isolation. It is consistent with the broader observation that no solid experimental consensus yet exists on when indirect retention helps and when it does not, and it sits alongside the hygienic concern raised in Section 3: an indirect retainer typically comprises a rest joined to the major connector by a minor connector, a design that covers additional tissue surface and may, for that reason alone, attract the same plaque-retention objections raised against other tissue-covering components [45].

6.3. Clinical Implication

The available studies are too limited to weaken the conventional recommendation in general: neither laboratory model reproduced the periodontal ligament or functional loading, and no clinical study has compared frameworks with and without an indirect retainer against displacement or abutment outcomes. What they do show is that the contribution of an indirect retainer to resisting displacement was smaller than that of the clasp and the guide planes [20], and that its effect on the abutments may depend on load [45]. The conventional rationale therefore continues to apply where lifting of the base is expected, as with long distal-extension bases [6]. Where the extension bases are short,

and guide planes are well prepared, or where an additional tissue-covering component would be difficult for the patient to clean, the case for routine inclusion is weaker, and the decision rests on clinical judgement rather than on evidence for or against the retainer.

7. Guide Planes and Frictional Retention

Guide planes are pairs of vertically parallel surfaces prepared on the proximal aspects of abutment teeth, oriented to define a single path of placement and displacement for the prosthesis. Their principal biomechanical function is described as converting what would otherwise be a poorly constrained seating movement into one restricted to a single axis, thereby reducing horizontal and rotational displacement of the framework during function and directing dislodging forces more evenly across the abutment teeth engaged along that axis [47].

The retentive contribution of guide planes has been quantified directly. In an in vitro comparison using extracted teeth mounted in a maxillary cast to simulate two bounded edentulous spaces, the preparation of guide planes alone increased the force required to dislodge an acrylic resin partial denture by a factor of 1.6, while modifying the fitting surfaces of the framework to contact the prepared guide planes intimately increased dislodging force by a factor of 10.2 relative to the unprepared condition [47]. The model represented tooth-supported (bounded) saddles, so the finding cannot be extended to distal-extension prostheses, in which the base moves under load. It derives from a single in vitro study with a small, specific sample and should be read as an order-of-magnitude estimate rather than a precise clinical figure; it has nonetheless been widely cited in the subsequent literature as evidence that the fit between framework and guide plane, rather than the mere presence of a prepared surface, is the principal determinant of frictional retention [48,49].

This distinction has direct clinical weight, because achieving intimate contact by conventional freehand tooth preparation is technique-sensitive and prone to inter-operator variability, motivating a recent shift toward guided and digital approaches to guide-plane preparation. Chairside devices and three-dimensionally printed or milled templates have been described to standardise the orientation and parallelism of prepared surfaces relative to a planned path of insertion [48,49]. Comparative in vitro work indicates that template-assisted preparation, whether by a rigid guide, a metal template fabricated by computer-aided design and computer-aided manufacturing, or more recently a robotic system, achieves closer parallelism and smaller angular deviation between guide planes than unguided freehand preparation, although freehand preparation performed by experienced operators can still achieve a clinically acceptable path of insertion [48–51]. A randomised comparison of template-aided versus freehand guide-plane preparation similarly found improved parallelism with the template, without a difference in overall chair time [50].

Beyond retention, guide planes are sometimes argued to be consistent with the hygienic principle set out in Section 3: a well-adapted guide plane and its corresponding proximal plate close the interproximal embrasure only to the depth necessary for frictional contact, without requiring bulk elsewhere in the framework to compensate for a poorly defined path of insertion. This argument is a hypothesis rather than a demonstrated benefit. The in vitro study cited above measured retention, not plaque accumulation or periodontal outcome [47], and no study identified here compared plaque or gingival indices around frameworks with and without prepared guide planes. It has also been suggested that better frictional retention could reduce the demand on other retentive elements and allow a shallower undercut, which would be compatible with the gingival clearance principle of Section 3; this too remains to be tested. In free-end prostheses, the base moves under load, so the benefit of intimate guide-plane contact for retention and hygiene cannot be assumed to match that in tooth-supported designs; the evidence is limited to one laboratory

study in which proximal guide planes helped to prevent lifting of a bilateral distal-extension base [20].

8. Direct Retention Systems

8.1. The Principle of Direct Retention

Direct retention is provided by the retentive arm of the clasp assembly, which must be flexible enough to deform as it passes the height of contour of the abutment during insertion, and to return passively to its original position once its terminal portion has entered the undercut, so that no continuous force is exerted on the tooth in the seated position [52]. The magnitude required of that force has been estimated experimentally. In an in vitro study measuring the forces exerted by food on artificial teeth during simulated mastication, the force ranged from 1.7 to 12.2 N per tooth depending on tooth type, occlusion and food, and the retention of wrought wire, circumferential and I-bar clasps after cyclic testing ranged from 2.9 to 14.5 N depending on the abutment and clasp type [53]. These are laboratory ranges, not clinical thresholds: the minimum retentive force required for function has not been established clinically, and the values quoted in later sections come from different designs, materials, and test set-ups (Table A2).

Because the patient inserts and removes the prosthesis several times each day, this behavior must persist over many thousands of cycles. Laboratory protocols simulating service life have applied 7200 cycles to represent five years [54], 15,000 cycles to represent ten years [55], and 20,000 cycles [52]. The first two conversions imply approximately four cycles a day, and 20,000 cycles correspond to about 13.7 years at the same rate, but this assumption derives from convention rather than from observation of patient behavior, and no clinical study has validated it. These figures should therefore be read as a shared convention for test design rather than as a demonstrated equivalence between laboratory cycles and years in service. The findings they generate are also not uniform: cast cobalt–chromium clasps showed a pronounced fall in retentive force during the earliest cycles followed by a more gradual decline, the residual force nonetheless remaining clinically adequate [54], whereas laser-sintered cobalt–chromium clasps of two circumferential designs showed little change in retention across 20,000 cycles [52].

8.2. The RPI System

The RPI assembly, comprising a mesial occlusal rest, a distal proximal plate, and a gingivally approaching I bar engaging a buccal undercut, was described by Krol as a clasp for abutment teeth carrying extension bases, with the explicit aims of minimising tooth coverage and reducing the stress transmitted to the abutment. Its mechanical logic follows from the rest position discussed in Section 5: with the fulcrum displaced mesially, occlusal loading of the extension base allows the proximal plate to move gingivally along the guide plane and the I bar to move mesio-apically, so that the retentive terminal disengages from the undercut rather than seating more deeply within it, the behaviour usually described as stress breaking. The design also serves the hygienic objective set out in Section 3, since the bar approaches the tooth from a gingival direction and contacts a small area of enamel, while the proximal plate replaces the broad reciprocal arm of a circumferential clasp [56]. These behaviours are properties of the assembly as a whole (abutment contour, proximal plate and retentive arm), not of the clasp type alone.

The anatomical conditions required for this behaviour are restrictive. Before turning to cross the gingival margin, the approach arm runs through the vestibule apical to the margin, conventionally about 3 mm from it in a technique description [31], so the design is precluded where the usable undercut lies closer than this to the gingival margin, where the buccal vestibule is shallow, where a frenal attachment occupies the path of the approach arm,

or where a pronounced soft-tissue undercut prevents the arm from being adapted without an unacceptable gap [31]. These constraints are consistently reported in the descriptive literature, but they are stated as clinical requirements rather than as thresholds established by comparative study; the 3 mm figure carries the same evidential status as the connector clearances discussed in Section 3, although it measures a different distance.

8.3. The RPA System

The RPA assembly was described by Eliason as an alternative for cases in which the RPI is contraindicated. It retains the mesial rest and the distal-proximal plate but substitutes a circumferential (Akers) retentive arm for the I bar, thereby avoiding the gingival approach and the tissue-related contraindications that accompany it. Eliason reported that the design essentially provides the same tooth release as the RPI, with the additional practical advantages of an arm that is easier for the patient to grasp and a form that dental laboratories can reproduce consistently [31].

This equivalence depends on a single condition of construction. The rigid body of the retentive arm must lie on the survey line as it passes from the proximal plate across the tooth, with only the tapered terminal portion dropping below it to engage the undercut. Where the whole arm is positioned above the height of contour, settling of the extension base under load causes the rigid arm to grip the tooth rather than release it, transmitting horizontal torque to the abutment. Eliason described the laboratory blackout procedure required to obtain the correct configuration, which indicates that the condition was recognised from the outset as one that fabrication could readily fail to meet [31].

Finite element comparison offers partial support with a qualification. In a three-dimensional analysis of mandibular Kennedy Class I frameworks, with and without mini-implant assistance, loaded bilaterally at 200 N, the RPI produced the lowest maximum von Mises stress across the supporting structures, whereas the RPA and a conventional Akers assembly with a distal rest produced values reported as not significantly different from one another, those for the Akers assembly being numerically the highest [57]. On this evidence, the analysis did not distinguish the RPA from the distal-rest Akers assembly, and the equivalence of the RPA to the RPI stated in the original clinical description is not reproduced computationally. The model was validated against a strain gauge model, but it was a static analysis of a single geometry, which limits generalisation [57].

8.4. Aesthetic and Prophylactic Variants

Two further designs recur in the literature. The cosmetic circumferential clasp for premolars with occlusal rest (C3PO) was proposed to eliminate the visible facial clasp arm on maxillary premolar abutments where aesthetic demands are high and attachment-retained solutions are financially inaccessible. The assembly begins at the guide-plane minor connector on the distal aspect of the premolar, passes at or above the survey line, and engages a mesiolingual undercut of 0.25 mm; support is provided by a distal occlusal rest, and bracing by the mesiolingual arm, the distal guide plane, and an optional short distofacial arm, giving encirclement beyond 180° [58]. Two qualifications are essential. The authors state explicitly that the assembly provides no stress release and is not recommended for the terminal abutment of a distal-extension prosthesis, proposing it instead for tooth-borne maxillary dentures. Furthermore, the source is a single clinical report published as a continuing-education article; the retentive values attributed to the design are inferred from earlier studies of other clasp types rather than measured for this one [58].

The backaction and reverse back-action clasps are both suprabulge circumferential retainers used with a mesial rest, differing in whether the retentive terminal engages a mesiobuccal or a distobuccal undercut. In an in vitro comparison of cobalt–chromium clasps

produced by direct metal laser sintering and subjected to 20,000 insertion and removal cycles, the change in retention was small for both designs, and the two differed only at 4000 and 5000 cycles [52]. The sample comprised six clasps on three extracted premolars, evaluated dry, so the finding supports comparable retention durability between the designs but does not bear on their relative gingival clearance.

8.5. Comparative Synthesis

The mechanical case for the mesial-rest assemblies is internally coherent and is supported by finite element evidence, but the clinical evidence is thinner than the confidence with which these designs are ordinarily recommended. A report from a long-standing institutional recall system, based on faculty observations rather than on a controlled comparison, found no trend favouring wrought wire, I-bar or L-bar assemblies, and concluded that all three perform satisfactorily when correctly selected and carefully applied [8]. The randomised comparison of mesial-rest I-bar and distal-rest circumferential designs described in Section 5.4 reached a similar conclusion, finding no difference in five-year success or abutment periodontal health [18]. The practical implication is that correct execution, specifically rest position, placement of the rigid arm relative to the survey line, and adequate gingival clearance, may be more consequential than the choice between the named assemblies.

9. Framework Materials and Digital Workflows

9.1. Digital Design and Manufacturing Workflows

The fabrication of removable partial denture (RPD) frameworks has historically depended on the lost-wax casting technique, a sequence in which dimensional accuracy is contingent upon operator skill at several successive stages. The introduction of computer-aided design and computer-aided manufacturing (CAD/CAM) has altered this dependency by transferring a substantial part of the process to a digital environment, where surveying, determination of the path of insertion, and blocking out of undesirable undercuts can be performed algorithmically rather than manually [5].

A fully digital workflow typically begins with intraoral or laboratory scanning, proceeds through virtual surveying and framework design in dedicated software, and terminates either in direct metal fabrication or in the printing of a castable pattern. The principal claim advanced for these workflows is not that they produce frameworks superior in kind, but that they reduce the variability introduced by manual wax manipulation and permit the design to be archived, revised, and reproduced [5].

9.2. Conventional Casting Versus Additive Manufacturing

Two distinct digital routes have emerged, and the evidence distinguishes between them. In the indirect route, the framework is designed digitally, and a castable pattern is printed, after which conventional casting proceeds as usual. In the direct route, the framework is built from alloy powder by selective laser melting (SLM).

A systematic review and meta-analysis of seven studies comparing fit accuracy across fabrication methods found greater misfit in CAD/CAM frameworks than in cast frameworks (standardized mean difference 1.23, 95% confidence interval 0.36 to 2.10). The indirect, pattern-printing route was numerically closer to the conventional result (standardized mean difference 1.15, 95% confidence interval −0.06 to 2.92) than the direct route (1.35, 95% confidence interval −0.27 to 2.44), but both subgroup intervals include zero, and the difference between the two digital techniques was not statistically significant ($p = 0.8482$) [11]. The authors nonetheless concluded that the misfit associated with both methods remained within the range considered clinically acceptable [11]. An earlier systematic review reached a compatible conclusion by a different route, reporting that frameworks produced by rapid

prototyping using selective laser melting showed the largest discrepancies among the digital techniques examined, while all analysed frameworks showed discrepancies below 311 µm, the value the review used as the boundary of clinically acceptable fit [59].

Two qualifications are necessary. First, the 311 µm figure is not an acceptance limit established against clinical outcome. Through the reviews that cite it, it traces to an early pilot study in which patterns designed by computer and produced by rapid prototyping were cast in cobalt–chromium, and the resulting frameworks were assessed for accuracy of fit, without clinical endpoints [60]. It therefore serves as a reference value for comparing fabrication methods, with the same evidential status as the clearances discussed in Section 3, and not as a threshold of clinical acceptability. Second, the primary studies in both reviews used heterogeneous measurement methods and small samples, so the pooled estimates should be read as indicating a direction rather than a magnitude. Within these limits, the interpretation of the difference matters more than the difference itself: a statistically detectable disadvantage in adaptation is not, on its own, evidence of clinical inferiority, and the available data do not support the exclusion of additive manufacturing from routine use on grounds of fit. For framework design, these data bear on the choice of fabrication route rather than on framework geometry.

9.3. High-Performance Polymers: PEEK, PEKK, and BioHPP

Metal allergy, concerns regarding corrosion and wear, and patient objections to visible metal components have together prompted interest in the polyaryletherketone (PAEK) family, principally polyetheretherketone (PEEK), polyetherketoneketone (PEKK), and the ceramic-reinforced composite marketed as BioHPP. Electrochemical studies show that the corrosion behaviour of framework alloys varies with the pH of the medium [61] and with minor differences in alloy composition [62–64], so the contrast between metal and polymer frameworks is not a simple binary one. These studies tested alloy samples rather than frameworks in function, do not address tribocorrosion at the clasp–tooth interface, and do not by themselves justify a change of framework material.

Retentive arms manufactured from these polymers generate lower retentive forces than cobalt–chromium clasps of comparable geometry, a direct consequence of their lower elastic modulus; the design response has been to modify cross-sectional dimensions rather than accept the reduction. A finite element optimization of PEEK clasp geometry identified combinations of base width and taper ratio that generated loads above 1.6 N, a figure the authors adopted from the literature as the lowest acceptable retentive force for a single clasp, while keeping maximum stress below the yield stress of the material evaluated (110 MPa); in fatigue testing equivalent to 10 years, the mean loads were 2.06–3.67 N for the PEEK groups and 8.26 N for the Co–Cr specimen at a displacement of 0.25 mm [65]. In vitro measurements gave values of a similar order: milled double Akers PEKK clasps (five per subgroup) produced initial retentive forces of 3.15 N to 3.51 N at undercut depths of 0.50 mm and 0.75 mm, compared with 2.40 N to 2.80 N at 0.25 mm, with no significant difference between the two deeper undercuts [66]; in an earlier comparison, resin clasps 1.5 mm thick gave 4.9–9.1 N and clasps 1.0 mm thick gave 1.2–3.1 N, against 11.3–16.3 N for Co–Cr [55]. These figures differ because they come from different designs, materials, undercut depths, and test set-ups; they are laboratory measurements, none has been related to clinical adequacy, and the 1.6 N design target, the 2.4–3.5 N PEKK values, and the food forces quoted in Section 8.1 should not be read as a single scale. Comparable work on PEEK and PEKK clasps found that the retentive force remained largely unchanged after cycling intended to represent 10 years of service [67]. In that comparison, the cross-section of the arm had a greater influence than undercut depth, although other studies found

higher retention at deeper undercuts [55,66]; the relevance of this to hygienic design has not been tested.

The same low modulus that limits retentive force also constrains the design of major connectors, and here the evidence differentiates within the PAEK family in a way that is often overlooked. A three-dimensional finite element analysis of a mandibular Kennedy Class I framework, in which a half pear-shaped lingual bar of identical dimensions (50 × 5 × 3 mm) was modelled in four materials under occlusal loads of 200 N vertically (five points of 40 N) and 150 N obliquely (first and second molars, bilaterally), reported maximum connector deformation of 0.180 mm for PEEK, 0.176 mm for PEKK, and 0.171 mm for BioHPP, against 0.029 mm for cobalt–chromium [68]. Deformation of this order is common to all three polymers. Stress transmission to the supporting mucosa, however, was not: maximum von Mises stress in the mucosa reached 3.03 MPa with PEEK and 2.30 MPa with BioHPP, both exceeding the 0.60 MPa recorded with cobalt–chromium, whereas PEKK transmitted 0.08 MPa, the lowest value of the four materials. The article reports a single maximum value for each material without stating whether it refers to the vertical load, the oblique load, or both, and the framework included RPA clasp assemblies on the first premolars and a cingulum rest on the canine [68]. The authors attributed this to a more favourable balance between stiffness and energy absorption in PEKK, and concluded that, when PEEK or BioHPP is used for a mandibular major connector, the connector must be enlarged beyond the dimensions appropriate to cobalt–chromium [68]. The PEKK mucosal value, about seven times lower than that of cobalt–chromium although the connector deformed six times more, was neither explained nor corroborated, and it should be regarded as an unreplicated result rather than as evidence of biological safety.

Four limitations qualify this finding. The analysis was static and linearly elastic, with viscoelastic and cyclic behaviour excluded; no direct experimental validation was performed, and model reliability was established instead by reproducing boundary and loading conditions from earlier analyses (the inferior border of the mandible was fixed, and the mesh of approximately 1.2 million tetrahedral elements was checked for convergence); and the results were derived from a single geometry in a single study [68]. Fourth, stress magnitudes were not compared with material strength: the maximum connector stress reported for PEEK (303 MPa) is almost three times the 110 MPa yield stress used for the same material in another finite element study [65], which a linearly elastic model cannot represent; the 646 MPa reported for cobalt–chromium was not compared with the proof stress of the alloy modelled; and no fatigue analysis was performed [68]. The absolute values therefore indicate the relative stiffness of the four connectors in this model, not their risk of failure. Earlier finite element comparisons reported higher mucosal stress with PEEK than with cobalt–chromium [36,69], but they used different geometries, loads and connector thicknesses, and agreement in direction between models built on similar assumptions is not independent confirmation of a clinical effect.

The models reviewed suggest that a PAEK framework should not be produced by substituting the polymer into a geometry designed for a metal alloy, since this was associated with increased connector flexure and, in most of the analyses, with greater mucosal loading for PEEK (Table 2). The direction of the mucosal effect is not uniform across studies, however [70]. Clinical use would therefore require deliberate dimensional compensation, principally an increase in connector bulk and optimisation of the cross-sectional profile to raise the second moment of area, a modification that may in turn affect tongue space and comfort. It should be noted that this compensation itself is a modelled requirement rather than a clinically validated protocol, and that the apparent advantage of PEKK rests at present on computational evidence from a single study. Long-term clinical studies of PAEK frameworks are considered in Section 11.3.

Table 2. Framework materials: modelled connector deformation and stress transmitted to the supporting mucosa. Values from Mostafa et al. [68] only: mandibular Kennedy Class I model with RPA clasp assemblies on the first premolars and a lingual bar of 50 × 5 × 3 mm, loaded with 200 N vertically (five points of 40 N) and 150 N obliquely; the article reports one maximum value per material without stating the load case. Values from other models are given in the notes and are not comparable in magnitude. Connector stresses for the polymers exceed the 110 MPa yield stress of PEEK [65]; see Section 9.3. All values derive from static, linearly elastic finite element analyses that were not experimentally validated; see Sections 11.1 and 11.3.

Material	Max. Connector Deformation (mm)	Max. von Mises Stress in Connector (MPa)	Max. von Mises Stress in Mucosa (MPa)	Sources	Design Implication
Cobalt–chromium (Co-Cr)	0.029	646.14	0.60	[68] [a]	Stiffest connector in [68]; mucosal stress lower than with PEEK and BioHPP but higher than with PEKK in [68]. Lower mucosal stress than PEEK in two other models [36,69] and higher in a third [70] ([a,c])
PEEK	0.180	303.28	3.03	[68] [a,c]	Most deformable connector and highest mucosal stress in [68], where connector enlargement was recommended; higher mucosal stress than Co-Cr in two other models [36,69] but not in [70] (n [a,c])
PEKK	0.176	295.29	0.08	[68] [b]	Lowest mucosal stress of all four materials, including Co-Cr, in a single analysis [68]; neither explained nor corroborated, so no conclusion on mucosal safety can be drawn
BioHPP	0.171	301.23	2.30	[68] [b]	Deformation and connector stress close to PEEK; mucosal pattern not yet corroborated

[a] Other models, with different geometry and load: Chen et al. [69] (full clinical framework, 120 N): framework 375.48 MPa (Co-Cr) vs. 99.54 MPa (PEEK); mucosa 0.59 vs. 0.74 MPa; displacement 0.46 vs. 0.69 mm. Weerayutsil et al. [36] (U-shaped palatal connector, 320 N; Co-Cr 1 mm and PEEK 2 mm thick): framework 107.99 vs. 11.7 MPa; mucosa 0.353 vs. 0.442 MPa; deformation 0.0082 vs. 0.0128 mm. Each value belongs to its own model; agreement in direction is not independent confirmation. [b] Single source [68]; no independent analysis of a PEKK or BioHPP major connector was identified. [c] Jantaban et al. [70] (unilateral mandibular distal extension, 200 N vertical load) report the opposite direction: Co-Cr exceeded PEEK at the abutment tooth (111.86 vs. 78.24 MPa), the periodontal ligament (0.126 vs. 0.097 MPa), and the residual mucosa (1.103 vs. 0.910 MPa). The major connector was a lingual bar in both models, so connector configuration does not account for the discrepancy; both models also included a distal rest and an indirect retainer. The two models differed in clasp design as well as in material, however, pairing Co-Cr with a wrought wire combination clasp and PEEK with a half-round Akers clasp, so the comparison does not isolate the effect of the framework material.

10. Survival, Patient-Reported Outcomes, and Implant-Assisted RPDs

10.1. Survival and the Definition of Failure

Statements about the survival of removable partial dentures (RPDs) are difficult to compare because the endpoint is defined differently across studies. This is demonstrated most directly by a ten-year evaluation of 886 metal-framework prostheses in 748 patients, in which survival was calculated from a single cohort using several failure criteria. When

abutment retreatment was taken as failure, approximately 40% of conventionally designed frameworks remained free of failure at five years and rather more than 20% at ten years; when failure was defined instead as replacement of the prosthesis or the patient ceasing to wear it, the corresponding figures were 75% and 50% [71]. The disparity is not a conflict between studies, but a consequence of what is being counted, and a survival figure quoted without its criterion is uninterpretable. For framework design, survival data bear mainly on two decisions: the choice between a metal framework and an acrylic base, and the provision made for maintenance.

Against this background, the largest recent estimate derives from a retrospective analysis of health records for 1893 prostheses in 1246 patients, with prostheses delivered between 2010 and 2021 and a median follow-up of 21.8 months (range 3–131.3). Metal-based RPDs had a median survival of 73 months (95% confidence interval 70–82) against 45 months (95% confidence interval 37–67) for acrylic resin RPDs. In a multivariable model, longer survival was associated with metal-based prostheses (hazard ratio 0.31, 95% confidence interval 0.23–0.42), restoration of both arches (0.67, 0.52–0.87), and maintenance care within three months (0.89, 0.83–0.96) and after three months (0.53, 0.46–0.61) of delivery [72]. Technical complications, chiefly clasp fracture, relining, and framework fracture, are frequent but largely reparable [73]. Two points follow. The association between a cast framework and longer survival corresponds to a difference of 28 months in median survival, not the categorical difference sometimes implied; it comes from observational data in which prosthesis type was not allocated at random, the short median follow-up limits the precision of the long-term estimates, and the intervals of the two medians nearly meet. And maintenance is associated with longevity, echoing the finding in Section 3 that the standard of plaque control, in addition to the design, appears to influence the periodontal outcome.

10.2. Patient-Reported Outcomes and Oral Health-Related Quality of Life

Patient-reported outcome measures (PROMs) capture what survival analysis does not. A systematic review of 35 studies reported satisfaction rates with RPDs ranging between 50% and 81%. This range should be read as the spread across heterogeneous instruments, populations, and follow-up intervals rather than as a pooled estimate, and its width is itself the finding: satisfaction is not a stable property of the prosthesis type. The same review identified older age, previous denture experience, and the presence of attachments or implants as associated with higher satisfaction and recorded that women reported greater satisfaction with appearance than men; pain, aesthetics, and difficulty with cleaning were the recurring sources of dissatisfaction [74].

Design factors were examined more specifically in a clinical study of 107 RPDs in 75 patients assessed with the McGill Denture Satisfaction Instrument, which recorded a mean satisfaction score of 8.2 ± 1.7 out of 10. Patients were more satisfied with maxillary than mandibular prostheses, with tooth-supported than distal-extension designs, and with prostheses retained by three or more clasps than by fewer. Two negative findings from the same study are relevant here: neither the framework material nor the presence of indirect retention was associated with satisfaction [46]. In a cross-sectional study of this size, the absence of an association does not demonstrate that the designs are equivalent, and satisfaction does not measure whether an indirect retainer prevents lifting of the base or protects the abutments (Section 6.2). Evidence on digital fabrication is limited. A systematic review of ten randomized trials reported higher satisfaction with digitally fabricated RPDs in two studies (mean difference 12.5 mm on a 100 mm scale, $p = 0.008$) and a pooled framework-fit estimate favoring conventional fabrication (standardized mean difference 0.49, $p = 0.02$); the authors considered the literature scarce and found clinically acceptable fit with both methods [75]. These results qualify the accuracy findings presented in Section 9.

10.3. Implant-Assisted Removable Partial Dentures

The rationale for placing an implant beneath a distal-extension base follows directly from the compliance mismatch set out in Section 4: an osseointegrated abutment posterior to the saddle converts a support outline that is essentially linear into a polygonal one, so that the prosthesis is no longer obliged to rotate about the terminal natural abutment. Finite element evidence is consistent with this mechanism. In a mandibular model comparing implant positions, the implant-supported configurations reduced stress in the abutment tooth structures and in the residual ridge mucosa and markedly reduced denture-base displacement relative to the conventional design [40]. A comparable analysis of bilateral distal free-end models found lower mucosal stress and vertical displacement with implant assistance, but also that an implant positioned at the second premolar produced non-physiological extrusive displacement of the abutment teeth under second-molar loading, on which basis the first molar region was recommended [76]. The benefit is therefore position-dependent rather than automatic.

Clinical data are more substantial here than elsewhere in this review. A systematic review and meta-analysis of implant-supported RPDs reported implant survival above 90% in all 16 included studies (334 participants), a mean marginal bone loss of 0.98 mm (95% confidence interval 0.61–1.36), and improved satisfaction and quality of life relative to conventional RPDs [77]; a further systematic review of implant-supported crown designs (ICRPD) reached a compatible conclusion while noting that the underlying evidence consists largely of retrospective studies and case reports [78]. The longest comparative cohort identified followed 88 patients with maxillary Kennedy Class I edentulism for five years across clasp-retained, attachment-retained, and mini-implant-retained designs. OHIP-14 scores, on which higher values indicate poorer OHRQoL, rose from 17.6 to 28.4 in the clasp-retained group, from 10.8 to 17.4 in the attachment-retained group, and from 10.9 to 13.1 in the mini-implant group, with no mini-implant failures recorded [79]. The authors themselves caution that allocation followed patient preference rather than randomization, so the difference may partly reflect self-selection; the finite element, meta-analytic, and longitudinal evidence is nonetheless directionally consistent, although they address different outcomes and cannot be combined. Summary of clinical evidence on survival are presented in Table 3.

Table 3. Summary of clinical evidence on survival, patient-reported outcomes, and implant-assisted designs.

Domain	Evidence	Key Finding	Main Limitation
Survival	Retrospective cohorts [71,72]	Metal frameworks were associated with longer survival than acrylic (median 73 vs. 45 months; hazard ratio 0.31, 95% confidence interval 0.23–0.42). Failure definition changes the figure two- to threefold.	No agreed failure definition; retrospective
PROMs	Systematic reviews, one cohort [46,74,75]	Satisfaction ranges 50–81%. No link to framework material or indirect retention in one cohort [46]. Higher satisfaction with digital fabrication in two trials, from scarce data [75]	Heterogeneous instruments; self-reported; single-cohort null findings

Table 3. *Cont.*

Domain	Evidence	Key Finding	Main Limitation
IARPD	FEA, reviews, one cohort [40,76–79]	Implant assistance lowers abutment/mucosal stress, but effect is position dependent. Implant survival > 90%. Smaller OHIP-14 deterioration than with clasp retention over 5 years (non-randomized comparison)	FEA unvalidated clinically; longest cohort non-randomized, self-selected

11. Limitations of the Current Evidence Base

11.1. The Modelling Assumptions of Finite Element Analysis

A substantial part of the mechanical evidence synthesized in this review is computational, and its interpretation depends on assumptions that are seldom satisfied in the mouth. The periodontal ligament is anatomically non-homogeneous and anisotropic, yet the vast majority of removable partial denture (RPD) finite element studies represent it as a homogeneous, isotropic, linearly elastic material for reasons of computational tractability [9]. This simplification is not neutral. Comparative work varying the boundary conditions and failure criteria applied to the periodontal ligament has shown that the stress values obtained shift according to the assumptions adopted, so that quantitative outputs are conditional on modelling decisions that are rarely justified in the source articles [38,39]. Models incorporating non-linear, load-dependent behavior of the ligament and the denture-bearing mucosa remain uncommon in this literature [40], the explicit viscoelastic representation of the mucosal interface by a Prony series being an exception rather than the norm [37].

Loading conditions are comparably simplified. Most published analyses apply a single static load, whereas mastication is cyclic, multidirectional, and variable in magnitude [9]; the fidelity with which mandibular kinematics are represented, and the complexity of the model itself, materially affect the results obtained [33]. Contact conditions are simplified as well: in one of the analyses summarized in Table 2, the interfaces between tooth, framework and mucosa were modelled as bonded, with no sliding or separation [36]. Saliva, which lubricates the interface between framework, tooth surface, and mucosa and modifies frictional behavior, is absent from the models examined here. Experimental validation is likewise infrequent: in the analysis on which Table 2 principally rests, reliability was established by reproducing boundary conditions reported in earlier studies rather than by direct measurement [68]. Findings such as the recurrent stress concentration at the rest–minor connector junction are therefore best read as indications of where load accumulates within a given geometry, not as measurements of what the supporting tissues experience clinically.

11.2. The Absence of a Validated Quality Appraisal Instrument for Finite Element Studies

A related difficulty is methodological rather than computational. Instruments exist for appraising the quality of in vitro dental research, most recently QUIN [80], and established tools address randomized and non-randomized clinical designs, but no validated instrument is available for assessing the methodological quality of dental finite element analyses. In consequence, studies reporting element type, convergence testing, material property sources, and validation against physical measurement cannot be formally distinguished from those reporting none of these, and both enter narrative syntheses with equivalent apparent weight. Given the volume of finite element work now published in prosthodontics, and its growing influence on design recommendations, the development and validation of a reporting and appraisal instrument specific to this method would be a worthwhile contribution to the

field. Until such an instrument exists, appraisal remains a matter of individual judgement exercised study by study, as it has been here.

11.3. The Absence of Long-Term Clinical Data for Polyaryletherketone Frameworks

The evidence supporting polyaryletherketone (PAEK) frameworks is almost entirely computational or in vitro. Retentive behavior has been characterized by finite element optimization [65] and by laboratory measurement of milled clasps under simulated insertion and removal cycling [66,67], and connector behavior rests on a single static analysis of one standardized geometry [68]. As noted in Section 8.1, the conversion of laboratory cycles into years of service follows a convention that has not been validated against patient behavior. No clinical cohort following PAEK frameworks over five to ten years was identified in the literature examined here, and the factors most likely to govern their durability, namely ageing in a mixed oral flora, water sorption, tribocorrosive wear, and the cumulative effect of repeated flexure of the major connector, have not been evaluated clinically. The dimensional compensation recommended in Section 9.3 is therefore a modelled requirement awaiting clinical confirmation.

11.4. Limitations of the Present Review

This review is narrative and critical rather than systematic. The literature search was described rather than exhaustive, covering two databases supplemented by citation chasing, and article selection was purposive, favoring studies with the longest follow-up, the clearest protocols, or explicit reporting of boundary conditions. No formal risk-of-bias assessment was undertaken, no duplicate screening or inter-rater agreement was performed, and only articles published in English were considered. Relevant work may therefore have been missed, and selection reflects the judgement of the authors. The search was logged only when it was repeated (Section 2), and only the records returned by three of the eight strings were screened specifically for contrary evidence. No formal grading system was applied, and no predefined rule beyond the working rule stated in Section 2 governed how clinical, computational and laboratory evidence were weighed against each other, so the weight given to individual studies reflects judgement. Three of the corrosion studies cited [62–64] include work by members of the author group; they are used only to illustrate alloy-to-alloy variability, and their relevance to frameworks in function is indirect. Reporting followed SANRA [17], which addresses these features but does not remove them.

12. Clinical Implications and Future Directions

12.1. Implications for Practice

The evidence reviewed here supports a set of working principles rather than a set of rules, and the confidence attached to each differs according to the kind of study from which it derives. They are grouped below by the kind of study supporting them.

Principles supported by clinical studies. Planned frameworks combined with intensive and repeatedly reinforced oral hygiene were followed by no significant periodontal deterioration over ten and subsequently twenty-five years in a prospective cohort [14,15], and maintenance care was associated with longer prosthesis survival in a retrospective cohort [72]; a systematic review found that pre-treatment and supportive care reduced biological complications [25]. Because design and maintenance were not varied independently, these studies do not show which contributed more. Maintenance therefore belongs to the treatment plan as an explicit component rather than as advice offered at delivery. Framework material was likewise associated with longer survival in one large retrospective cohort, with a difference in median survival of 28 months [72]. Coverage of the free gingival margin that the design does not require is best avoided, since in a short experimental model

(10 subjects, 21 days) such coverage was followed by gingival inflammation without a detectable increase in plaque [12], and lingual plates were associated with more inflammation or deeper probing than bars in small crossover studies [13,22,23]; under regular recall, however, a 30-month comparison found no difference in attachment loss [21]. These findings support restraint in coverage; they do not identify an optimal framework geometry. Where complete assemblies have been compared in a randomised trial, mesial-rest I-bar and distal-rest circumferential designs had similar five-year success and abutment periodontal health [18].

Principles supported by laboratory or computational studies alone. In laboratory and finite element models of distal-extension prostheses, an assembly with a mesially positioned rest and a retentive arm able to move as the base settles directed load closer to the long axis of the abutment [7,34], and the direction of the force on the abutment changed accordingly in one subject in vivo [42]; the preference holds for the assemblies, support conditions and loads modelled, and the randomized comparison of complete assemblies found no clinical difference [18]. In one static finite element model of a maxillary Kennedy Class II framework under 60 N, a contralateral rest on the second premolar gave the smallest saddle displacement under oblique load and a canine or first premolar the largest, with no effect on mucosal stress [9,43]; this is a reason to prefer a premolar or molar where the choice is otherwise equal, not a rule. In the models reviewed, a polyaryletherketone framework requires deliberate dimensional compensation rather than substitution into a geometry designed for an alloy [68]. In finite element models, implant assistance beneath a distal-extension base was associated with lower loading of the natural abutment, but the benefit was position-dependent rather than automatic [40,76]. Agreement in direction between models built on similar assumptions does not establish a clinical effect, and its magnitude is not established.

Values that remain conventions. The clearances of about 3 mm for mandibular connectors and about 6 mm for the borders of maxillary connectors [29,30], the distance of about 3 mm at which a bar-clasp approach arm runs apical to the gingival margin [31], the 311 µm reference value for framework misfit [59,60], and the conversion of laboratory insertion cycles into years of service were adopted from earlier practice rather than derived by comparing graded alternatives against outcome. They are serviceable as design targets and should be stated as such.

Two findings inform planning by restraining it. In laboratory models, an indirect retainer contributed less to resisting displacement of the base than the clasp and the guide planes [20], and its effect on the primary abutment depended on load [45]; no clinical study has tested it against displacement or abutment outcomes. It remains indicated where lifting of a long extension base is expected, and its routine addition elsewhere warrants case-by-case justification. Similarly, long-term recall of wrought wire, I-bar, and L-bar assemblies disclosed no trend favoring any one of them [8], which suggests that correct execution, specifically rest position, placement of the rigid arm relative to the survey line, and adequate gingival clearance, may matter more than the choice between named assemblies. These principles are summarized as a design sequence in Figure 3, which is a summary aid rather than a clinical protocol; each step carries a label for the type of study supporting it, and Table 4 gives the study design, endpoint, and references for each recommendation.

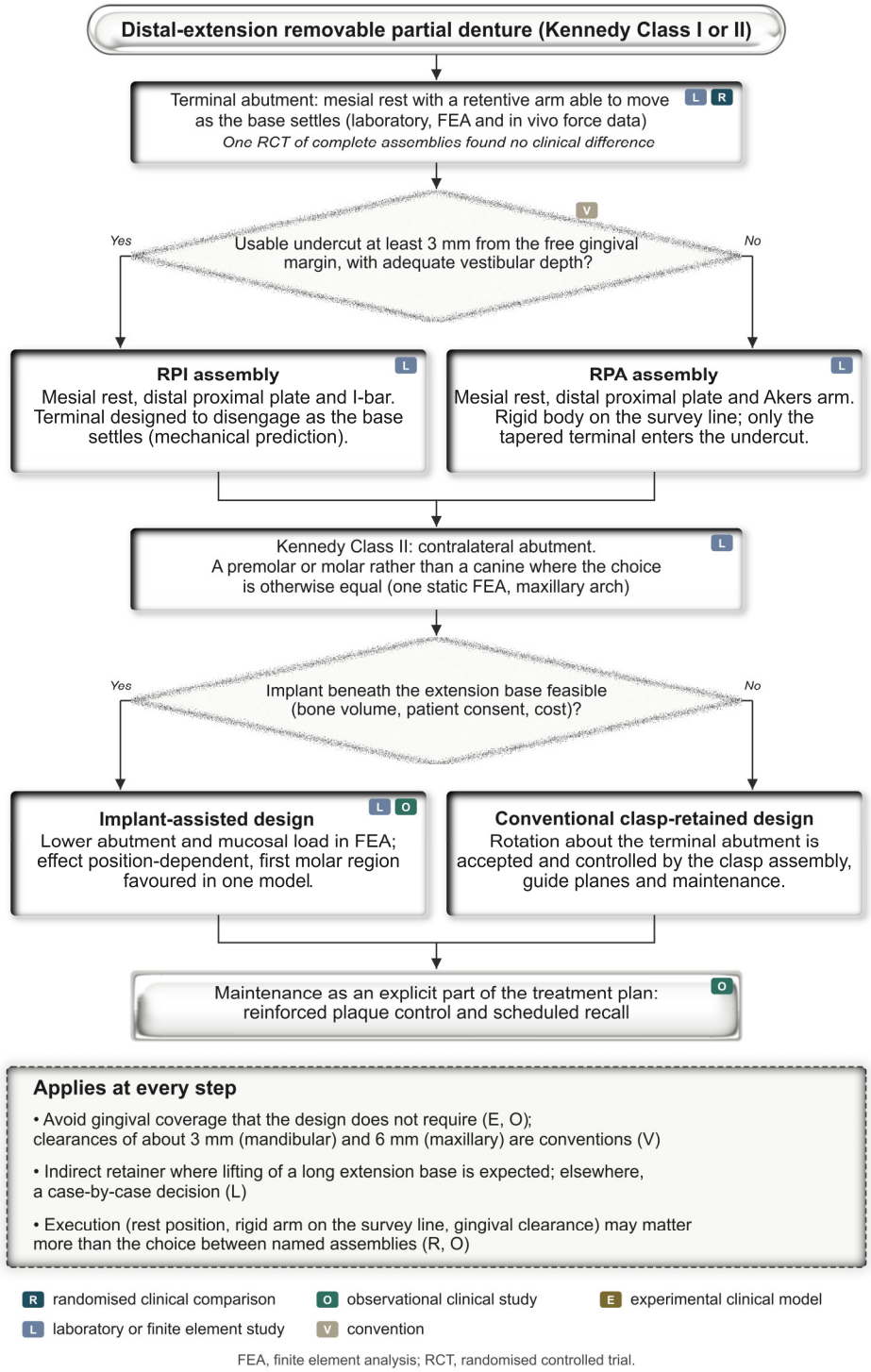


Figure 3. Design sequence for a distal-extension removable partial denture, with each recommendation labelled by the design of the studies supporting it: R = randomized or controlled clinical comparison; O = observational clinical study; E = short-term experimental clinical model; L = laboratory or finite element study; V = value adopted by convention rather than derived by comparing graded alternatives against outcome. Where R appears, the trial compared complete assemblies and found no difference (Section 5.4). Study designs, endpoints and supporting references [7–9,12–15,18,20–23,25,29–31,34,40,42,43,45,56,57,72,76–79] are given in Table 4.

Table 4. Study design, endpoints and references behind each recommendation in Figure 3. E, experimental clinical model; O, observational clinical study; R, randomized or controlled clinical comparison; L, laboratory or finite element study; V, convention; FEA, finite element analysis; PDL, periodontal ligament; RCT, randomised controlled trial.

Recommendation	Supporting Study Designs	Endpoints	References
Avoid gingival coverage that the design does not require	Short-term experimental models (E); small crossover trials; one 30-month comparative cohort (O)	Gingival index, plaque, probing depth, attachment loss; 21 days to 30 months	[12,13,21–23]
Plan maintenance as part of treatment	Prospective cohorts; retrospective survival cohort (O)	Periodontal status at 10 and 25 years; prosthesis survival	[14,15,72]
Mesial rest with a releasing retentive arm on the terminal abutment	Laboratory model; static FEA (L); in vivo force in one subject; one RCT of complete assemblies (R)	Abutment displacement, PDL stress, force direction; 5-year success and abutment periodontal health (no difference)	[7,18,34,42]
RPI or RPA assembly according to undercut position and vestibular depth	Descriptive reports; static FEA (L); RCT and institutional recall (R, O)	Stress in supporting structures; 5-year success; clinical observation (no difference between assemblies)	[8,18,31,56,57]
Contralateral abutment: premolar or molar rather than canine	One static FEA of a maxillary arch under 60 N (L)	Saddle displacement; mucosal stress (no difference)	[9,43]
Indirect retainer where lifting of a long extension base is expected	Two laboratory models without PDL (L); one cross-sectional satisfaction study	Base displacement; abutment deformation; satisfaction (no association)	[20,45,46]
Implant beneath the extension base, position-dependent	Static FEA (L); meta-analysis of single-arm studies; non-randomized 5-year cohort (O)	Stress and displacement; implant survival and bone loss; OHIP-14	[40,76–79]
Connector clearances: about 3 mm from the gingival margin to the superior border of mandibular major connectors and 6 mm to the borders of maxillary major connectors. Bar clasp: approach arm kept about 3 mm apical to the gingival margin before crossing it	Convention (V)	Not tested against outcome	[29–31]

12.2. Directions for Future Research

Five priorities follow from the limitations set out in Section 11.

First, the preference for a mesially placed rest rests on a laboratory measurement of tooth displacement and on finite element confirmation of the same comparison [7,34], and the one randomized trial identified compared complete assemblies with different clasps rather than rest positions alone [18]. A prospective clinical comparison of mesial and distal rest positions with the clasp assembly held constant, with abutment survival, mobility, and marginal bone level as endpoints and a follow-up long enough for cumulative loading to

express itself, would evaluate the most widely taught rule in this field against the outcome it is intended to protect.

Second, as noted in Section 11.2, no validated instrument exists for appraising the methodological quality of dental finite element studies. Developing and validating such an instrument, addressing at minimum element type and mesh convergence, the provenance of material properties, the boundary conditions applied, and whether the model was validated against physical measurement, would allow reviewers to weight computational evidence rather than accept it at face value.

Third, finite element models of removable partial dentures would gain clinical relevance through cyclic, multidirectional loading; nonlinear representation of the periodontal ligament and denture-bearing mucosa; inclusion of the salivary interface; and validation against experimental measurements. Analyses meeting these conditions remain uncommon [37–39], and the recurrent stress concentrations identified in Section 4 would be more persuasive if reproduced under them.

Fourth, prospective cohorts following polyaryletherketone frameworks for five to ten years are required before the material can be recommended on the same basis as cast cobalt-chromium. Such studies should record connector deformation over time, the mucosal response beneath the connector, loss of retention, and fracture, and should establish whether the dimensional compensation derived computationally [68] proves sufficient in service.

Fifth, agreement is needed on how failure of a removable partial denture is to be defined, since survival calculated from a single cohort differs markedly according to the criterion adopted [71].

13. Conclusions

This review has examined how mechanical and hygienic requirements are balanced in removable partial denture framework design, and on what evidence. The evidence is uneven in kind. The association between coverage of the gingival tissues and gingival inflammation is the part best supported by clinical observation, although the experimental studies are small and short and, under regular recall, coverage was not followed by attachment loss. The longitudinal cohorts combined planned frameworks with intensive maintenance and cannot separate the two; they support building maintenance into treatment but do not show that any framework geometry is clinically optimal.

Much of the remainder is computational. The preference for a mesially positioned rest, the selection of the contralateral abutment, the dimensional compensation required of polyaryletherketone connectors, and the mechanical advantage attributed to implant assistance are each supported mainly by laboratory measurement or finite element simulation, whose direction is generally consistent, but whose clinical magnitude remains unestablished. Several of the values that circulate as design targets in this field are conventions adopted from earlier practice rather than thresholds derived by comparing graded alternatives against outcomes, and they are best stated as such. Where complete designs have been compared clinically, in a randomised trial of mesial-rest and distal-rest assemblies and in long-term recall of alternative retentive assemblies, no clear advantage of the mechanically preferred option was found; for indirect retention, no clinical comparison exists.

The priorities indicated are therefore clinical validation of what computational and laboratory work has suggested, and improvement of the computational models themselves (non-linear tissue behaviour, cyclic loading and experimental validation): prospective comparison of rest positions, of framework materials in service, and of retentive designs, assessed against periodontal and abutment outcomes over intervals long enough for cumulative loading to express itself. A parallel requirement is methodological, namely agreement on how failure of a removable partial denture is to be defined, and an instrument by which

the quality of finite element studies can be appraised rather than assumed. For the practicing clinician, the most secure messages are to avoid gingival coverage that the design does not require, to build maintenance into the treatment plan, and to treat the remaining design rules as reasoned conventions to be balanced case by case rather than as proven thresholds. Mechanical and hygienic requirements are complementary, and comparative clinical evidence for choosing between them remains limited.

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Appendix A

Table A1 gives the search strings, the number of records returned, and the selection approach, and Table A2 summarizes the principal studies discussed, with their design, model parameters, main findings, and limitations. Reference numbers in Table A2 refer to the main reference list. CI, confidence interval; SMD, standardized mean difference; PDL, periodontal ligament.

Table A1. Search concepts and selection approach for this narrative review.

Item	Description
Databases	MEDLINE (via PubMed) and Scopus. Initial searches to July 2026 were not logged; the search was repeated and logged on 15 November 2026 (PubMed) and on 16 November 2026 (Scopus).
Concept block 1: device	removable partial denture(s)
Concept block 2: design elements	occlusal rest; clasp; major connector; minor connector; guide plane; indirect retention
Concept block 3: materials and fabrication	cobalt–chromium; polyaryletherketones; CAD/CAM; selective laser melting
Concept block 4: methods and outcomes	finite element analysis; von Mises stress; retentive force; framework fit; survival; patient-reported outcomes
String A: gingival coverage (Section 3)	(“Denture, Partial, Removable”[MeSH] OR “removable partial denture”[tiab] OR “removable partial dentures”[tiab]) AND (gingivitis[tiab] OR gingival[tiab] OR periodontal[tiab] OR plaque[tiab] OR “Periodontal Index”[MeSH]) AND (design[tiab] OR connector[tiab] OR connectors[tiab] OR coverage[tiab]) AND english[la]. PubMed: 119.
String B: finite element analysis (Section 4)	(“Denture, Partial, Removable”[MeSH] OR “removable partial denture”[tiab] OR “removable partial dentures”[tiab]) AND (“finite element”[tiab] OR “Finite Element Analysis”[MeSH]) AND english[la]. PubMed: 105.

Table A1. *Cont.*

Item	Description
String C: rest position (Section 5)	(“Denture, Partial, Removable”[MeSH] OR “removable partial denture”[tiab] OR “removable partial dentures”[tiab]) AND (“occlusal rest”[tiab] OR “occlusal rests”[tiab] OR “rest position”[tiab] OR “rest seat”[tiab] OR “mesial rest”[tiab] OR “distal rest”[tiab]) AND english[la]. PubMed: 127.
String D: indirect retention (Section 6)	(“Denture, Partial, Removable”[MeSH] OR “removable partial denture”[tiab] OR “removable partial dentures”[tiab]) AND (“indirect retainer”[tiab] OR “indirect retainers”[tiab] OR “indirect retention”[tiab] OR “cross-arch”[tiab] OR “contralateral abutment”[tiab]) AND english[la]. PubMed: 50.
String E: guide planes (Section 7)	(“Denture, Partial, Removable”[MeSH] OR “removable partial denture”[tiab] OR “removable partial dentures”[tiab]) AND (“guide plane”[tiab] OR “guide planes”[tiab] OR “guiding plane”[tiab] OR “guiding planes”[tiab] OR “guide surface”[tiab]) AND english[la]. PubMed: 69.
String F: direct retention (Section 8)	(“Denture, Partial, Removable”[MeSH] OR “removable partial denture”[tiab] OR “removable partial dentures”[tiab]) AND (“Dental Clasps”[MeSH] OR clasp[tiab] OR clasps[tiab] OR RPI[tiab] OR RPA[tiab] OR “I-bar”[tiab]) AND (retention[tiab] OR “retentive force”[tiab] OR fatigue[tiab] OR stress[tiab]) AND english[la]. PubMed: 261.
String G: materials and fabrication (Section 9)	(“Denture, Partial, Removable”[MeSH] OR “removable partial denture”[tiab] OR “removable partial dentures”[tiab]) AND (framework[tiab] OR frameworks[tiab]) AND (PEEK[tiab] OR PEKK[tiab] OR polyaryletherketone[tiab] OR “selective laser melting”[tiab] OR “computer-aided”[tiab] OR CAD-CAM[tiab] OR fit[tiab] OR misfit[tiab] OR accuracy[tiab]) AND english[la]. PubMed: 247.
String H: outcomes (Section 10)	(“Denture, Partial, Removable”[MeSH] OR “removable partial denture”[tiab] OR “removable partial dentures”[tiab]) AND (survival[tiab] OR longevity[tiab] OR “patient satisfaction”[tiab] OR “quality of life”[tiab] OR OHIP[tiab] OR “implant-assisted”[tiab] OR “implant-supported”[tiab]) AND english[la]. PubMed: 754.
Scopus strings	All strings had the form TITLE-ABS-KEY(“removable partial denture*”) AND [middle block] AND LANGUAGE(english); the middle blocks were: A, TITLE-ABS-KEY(gingivitis OR gingival OR periodontal OR plaque) AND TITLE-ABS-KEY(design OR connector* OR coverage) (313); B, TITLE-ABS-KEY(“finite element”) (135); C, TITLE-ABS-KEY(“occlusal rest*” OR “rest position” OR “rest seat” OR “mesial rest” OR “distal rest”) (166); D, TITLE-ABS-KEY(“indirect retain*” OR “indirect retention” OR “cross-arch” OR “contralateral abutment”) (51); E, TITLE-ABS-KEY(“guide plane*” OR “guiding plane*” OR “guide surface*”) (66); F, TITLE-ABS-KEY(clasp* OR RPI OR RPA OR “I-bar”) AND TITLE-ABS-KEY(retention OR “retentive force” OR fatigue OR stress) (420); G, TITLE-ABS-KEY(framework*) AND TITLE-ABS-KEY(PEEK OR PEKK OR polyaryletherketone* OR “selective laser melting” OR “computer-aided” OR “CAD-CAM” OR fit OR misfit OR accuracy) (297); H, TITLE-ABS-KEY(survival OR longevity OR “patient satisfaction” OR “quality of life” OR OHIP OR “implant-assisted” OR “implant-supported”) (915). Run on 16 November 2026.
Screening for contrary evidence	Titles of the records returned by strings A, C and D (279 unique in PubMed; 219 further records found only in Scopus), and abstracts where needed, were screened for studies reporting results contrary to the principal claims. Added: [18–25].
Supplementary methods	Backward and forward citation chasing of key articles. No journals were hand-searched.
Limits	No lower date limit (earliest source retained: 1963). English language only.

Table A1. *Cont.*

Item	Description
Records retrieved	Repeated PubMed search: 1445 unique records (A 119, B 105, C 127, D 50, E 69, F 261, G 247, H 754; a record may appear under more than one string). Scopus: 1846 unique records (A 313, B 135, C 166, D 51, E 66, F 420, G 297, H 915); about 2105 unique records across both databases after removal of duplicates by title. No flow diagram is provided.
Selection	Purposive. Priority was given to clinical studies with the longest follow-up, finite element analyses reporting model validation and boundary conditions, and in vitro studies with clearly defined protocols; systematic reviews were used as secondary sources. Selection was made by the authors without independent duplicate screening or a formal procedure for resolving disagreements.
Weighing of evidence	Working rule, not a grading system: clinical studies were given more weight than computational or laboratory studies addressing the same question; observational and randomized clinical data were distinguished; computational studies were considered more informative where boundary conditions, material models and validation status were reported.

Table A2. Principal studies discussed: design, model parameters, main findings and limitations. A study is listed when a numerical value or a design recommendation in the text depends on it; "validated" denotes comparison with physical measurement.

Study (Ref.)	Design and Model Parameters	Main Findings	Limitations and Validation
Finite element analyses			
Muraki 2004 [34]	3D model of two mandibular premolars; mesial or distal rest on the second premolar. Zero displacement on the outer surface of the periodontal ligament (PDL) and first premolar; rest moved 0.05 mm apically, horizontal movement free or restricted.	Largest values with a distal rest free to move: 42 µm distal displacement (buccal cusp) and 0.35 MPa principal compressive stress in the PDL; all within physiological limits.	Single vertical displacement; premolar segment only; validation not stated in the abstract.
Zarrati 2015 [41]	3D model, mandibular Kennedy Class I modification 1; isolated second premolar with mesial rest, with mesial and distal rests, or non-isolated abutment with mesial rest. 26 N bilaterally at first molar sites.	Maximum von Mises stress 30 MPa (mesial rest) versus 15 MPa (mesial and distal rests) in the isolated-abutment models; both rests recommended.	Static load; no distal-rest-only model; validation not stated in the abstract.
Wada 2006 [43]	3D maxillary Kennedy Class II framework; contralateral rest on canine, first premolar, second premolar or first molar; rests restrained; 60 N vertical or buccally oblique load on the extension base [9].	Canine and first premolar rests less resistant to oblique load; smallest saddle displacement with second premolar; mucosal stress insensitive to abutment.	Static; single geometry; restrained rests, no PDL; validation not stated in the abstract.
Rungsiyakull 2022 [57]	3D mandibular Kennedy Class I models with RPA, RPI, Akers (distal rests) or no clasp, with and without bilateral mini-implants. 200 N vertical, bilateral.	RPI lowest stress; Akers highest; RPA and Akers not significantly different.	Static, single geometry. Validated against a strain gauge model (error below 10% for most measurements).

Table A2. *Cont.*

Study (Ref.)	Design and Model Parameters	Main Findings	Limitations and Validation
Mostafa 2025 [68]	3D mandibular Kennedy Class I; lingual bar 50 × 5 × 3 mm in Co-Cr, PEEK, PEKK or BioHPP. Linear static; 200 N vertical and 150 N oblique; inferior mandibular border fixed; about 1.2 million tetrahedral elements, convergence checked; isotropic, homogeneous, linear elastic.	Deformation 0.029 mm (Co-Cr) versus 0.171–0.180 mm (polymers). Mucosal stress 0.60 MPa (Co-Cr), 3.03 (PEEK), 2.30 (BioHPP), 0.08 (PEKK).	No direct experimental validation; boundary conditions reproduced from earlier work; single geometry; PEKK mucosal value uncorroborated.
Chen 2019 [69]	3D model from one patient, four RPD designs, three framework materials (Co-Cr, Ti-6Al-4V, PEEK). 120 N vertical load on the first molars; friction coefficients 0.1 and 0.01 (base–mucosa).	Framework stress 375.48 MPa (Co-Cr) versus 99.54 MPa (PEEK); mucosal stress 0.59 versus 0.74 MPa; free-end displacement 0.46 versus 0.69 mm.	Single patient-derived geometry; validation not stated in the abstract.
Weerayutsil 2025 [36]	3D maxillary bilateral distal extension with U-shaped palatal connector; Co-Cr 1 mm versus PEEK 2 mm. 320 N vertical in total; base of maxilla fixed; bonded interfaces; isotropic, homogeneous, linear elastic.	Framework stress 107.99 MPa (Co-Cr) versus 11.7 MPa (PEEK); mucosal stress 0.353 versus 0.442 MPa; deformation 0.0082 versus 0.0128 mm.	No experimental validation; bonded contacts; different thickness for the two materials.
Jantaban 2025 [70]	3D left mandibular distal extension; Co-Cr with wrought wire combination clasp versus PEEK with half-round Akers clasp; lingual bar, distal rest, indirect retainer. 200 N (5 × 40 N) vertical, unilateral; about 944,000 elements; fixed bone sections; mucosa–base friction 0.4.	Co-Cr higher than PEEK: abutment 111.86 versus 78.24 MPa; PDL 0.126 versus 0.097 MPa; mucosa 1.103 versus 0.910 MPa.	Clasp design differs between models; vertical unilateral load; isotropic, linear elastic; no experimental validation.
Murashima 2024 [76]	3D model from CT of one patient with a unilateral defect; bilateral distal free-end RPD with a titanium implant in the first premolar, second premolar, or first molar region. 200 N vertical.	Mucosal stress and base displacement smaller with implants (second premolar and first molar regions); abutment extrusion with the second premolar implant under second molar load.	Static load; single patient geometry; validation not stated in the abstract.
Nakamura 2025 [40]	3D mandibular model; RPI clasps; 10 mm implant at site 45, 46 or 47; non-linear properties assessed for mucosa and PDL.	Lower abutment stress, mucosal stress and base displacement with implants; least displacement at site 46.	Single model; validation not stated in the abstract.
Ramakrishnan 2021 [37]	3D RPD model with a viscoelastic adhesive layer between base and mucosa (Prony series); simulated bite force on one segment.	Mucosal contact pressure 0.15 MPa with adhesive versus 0.25 MPa without.	Adhesive-layer model, not a framework comparison.
Peng 2020 [65]	72 rod-shaped models analyzed by finite elements, followed by fatigue testing of PEEK and Co-Cr specimens; 1.6 N adopted from the literature as the lowest acceptable retentive force per clasp; PEEK yield stress 110 MPa.	After fatigue testing equivalent to 10 years, mean loads 2.06–3.67 N (PEEK groups) versus 8.26 N (Co-Cr, 0.25 mm).	Rod specimens, not complete clasps; laboratory only.

Table A2. *Cont.*

Study (Ref.)	Design and Model Parameters	Main Findings	Limitations and Validation
Laboratory studies			
Kratochvil 1963 [7]	Laboratory measurement of abutment tooth movement on an instrumented mandibular model; distal versus mesial rest under a simulated distal-extension load.	Distal rest: posterior tipping of the abutment. Mesial rest: anterior tipping.	Laboratory model; no clinical outcomes.
Frank 1977 [20]	Mandibular bilateral distal-extension framework lifted from a model; clasp type, indirect retainer location and rest position changed in turn; base displacement and removal force measured electronically.	Indirect retainer of limited use against lifting; clasp type had the greatest influence; guide planes helped; mesial rests did not reduce indirect retention.	Laboratory model; no PDL or functional loading.
Oliveira 2025 [45]	Electronic speckle pattern interferometry on a plastic master model; Kennedy Class I mandibular RPD with or without an indirect retainer on tooth 44. Tensile loads 0.15–0.70 N perpendicular to the ridge.	Contralateral abutments deformed more with the retainer; effect on the adjacent abutment depended on load (less deformation at 0.15 N, more at 0.30 N).	Acrylic model without PDL simulation; very low loads; single model.
Mothopi-Peri 2018 [47]	Extracted teeth in a maxillary cast with two bounded saddles; acrylic resin RPD with no guide planes, with guide planes, and with guiding surfaces contacting the guide planes.	Retention increased 1.6 times (guide planes only) and 10.2 times (intimate contact).	Tooth-supported saddles only; single laboratory study.
Alageel 2019 [53]	Universal testing machine: forces of food on acrylic teeth during simulated mastication; retention of wrought wire, circumferential and I-bar clasps after cycling.	Food forces 1.7–12.2 N per tooth; clasp retention 2.9–14.5 N. Prediction algorithm tested on 36 RPDs (sensitivity 96%, specificity 100%).	Laboratory values, not clinical thresholds.
Cheng 2010 [54]	Three cast Co-Cr alloys; undercuts 0.25 and 0.50 mm; 7200 insertion cycles (5 years).	Fall in retentive force during early cycles, then gradual decline; residual force adequate.	Conversion of cycles to years is a convention.
Tannous 2012 [55]	PEEK, PEKK, POM and Co-Cr clasps on premolar crowns; undercuts 0.25 and 0.50 mm; 15,000 cycles (10 years).	Resin clasps 1.5 mm: 4.9–9.1 N; 1.0 mm: 1.2–3.1 N; Co-Cr 11.3–16.3 N.	Laboratory only; conversion convention.
Peng 2024 [66]	Thirty CAD/CAM double Akers PEKK clasps, two designs, undercuts 0.25, 0.50 and 0.75 mm (five per subgroup); 15,000 cycles.	Initial retention 3.15–3.51 N (0.50 and 0.75 mm) versus 2.40–2.80 N (0.25 mm); no significant fall after cycling.	Small sample; laboratory only.
Anes 2023 [52]	Laser-sintered Co-Cr back-action and reverse back-action clasps; 20,000 cycles.	Little change in retention; designs differed only at 4000 and 5000 cycles.	Small sample; laboratory only.
Clinical studies			
Orr 1992 [12]	Ten subjects wear acrylic baseplates with connectors in varied relation to the gingival margin, 12 h daily for 21 days.	Gingival index increased where the margin was covered; no increase in plaque.	Ten subjects; experimental, short-term.

Table A2. *Cont.*

Study (Ref.)	Design and Model Parameters	Main Findings	Limitations and Validation
McHenry 1992 [13]	Single-blind crossover experimental gingivitis trial: lingual plate versus cingulum bar, 21 days each.	Greater gingival inflammation with the lingual plate.	Experimental model; short-term.
Ao 2013 [22]	Crossover: 14 subjects, lingual bar and lingual plate, 8 weeks each, after debridement.	Greater probing depth with the plate; no difference in subgingival periodontal pathogens.	Small; short-term.
Ogunrinde 2014 [23]	Crossover: 15 patients, Kennedy Class III, lingual bar and lingual plate, 3 months each.	No difference in plaque index; lower gingival index with the bar.	Small; short-term.
Akaltan 2005 [21]	36 patients with distal-extension RPDs, lingual plate or lingual bar, regular recall, 30 months.	More plaque with the plate; no difference in probing depth, gingival index, or attachment loss; improvement in both groups except recession.	Allocation method not stated in the abstract; intermediate duration.
Yeung 2000 [26]	Survey of 87 wearers of Co-Cr RPDs after 5–6 years; one calibrated examiner.	Plaque, gingivitis and recession concentrated within 3 mm of the denture; mucosal lesions uncommon.	Cross-sectional; association only.
Bergman 1982, 1995 [14,15]	Longitudinal cohort followed for 10 and 25 years; most patients with lower distal-extension dentures; intensive, repeatedly reinforced oral hygiene.	No significant periodontal deterioration.	Not designed to compare framework designs.
Kapur 1994, 1997 [18,19]	Randomized trial: 134 patients, Kennedy Class I and II; mesial rest with I-bar versus distal rest with cast circumferential clasp; 5 years.	Success 76.6% (bar) versus 71.3% (circumferential), not significant; no difference in nine periodontal measures; masticatory scores similar over follow-up.	Compares complete assemblies, not rest position alone.
Vermeulen 1996 [71]	886 metal-framework RPDs in 748 patients, followed 5–10 years (288 dropouts); survival by retreatment, non-wearing or replacement.	Free of abutment retreatment: 40% at 5 years, over 20% at 10 years; replacement or non-wearing: 75% and 50%.	Single institution; endpoint-dependent results.
Ahmed 2024 [72]	Retrospective record review: 1893 RPDs, 1246 patients, 2010–2021; median follow-up 21.8 months (3–131.3); mixed-effects Cox models.	Median survival 73 (95% CI 70–82) versus 45 (37–67) months; hazard ratio 0.31 (0.23–0.42) for metal-based RPDs.	Observational; short median follow-up; confounding possible.
Alageel 2020 [46]	75 patients with 107 RPDs; McGill Denture Satisfaction Instrument.	Mean satisfaction 8.2 ± 1.7 of 10; higher for maxillary, tooth-supported and three or more clasps; no association with material or indirect retention.	Cross-sectional.
Peršić Kiršić 2025 [79]	88 patients, maxillary Kennedy Class I; clasp-, attachment- or mini-implant-retained RPD; 5 years; ANCOVA adjusted for baseline score, age, gender and education.	OHIP-14: 17.6 to 28.4 (clasp), 10.8 to 17.4 (attachment), 10.9 to 13.1 (mini-implant); no mini-implant failures.	Non-randomized; allocation by patient preference.

Table A2. *Cont.*

Study (Ref.)	Design and Model Parameters	Main Findings	Limitations and Validation
Systematic reviews			
Mai 2022 [11]	Meta-analysis of seven studies of CAD/CAM versus cast framework fit.	Overall SMD 1.23 (95% CI 0.36–2.10); indirect 1.15 (−0.06 to 2.92); direct 1.35 (−0.27 to 2.44); difference between digital routes $p = 0.8482$.	Heterogeneous measurement methods; small samples.
Almufleh 2024 [75]	Ten randomized trials; four in the fit meta-analysis.	Higher satisfaction with digital RPDs in two studies (12.5 mm on a 100 mm scale, $p = 0.008$); fit SMD 0.49 favoring conventional ($p = 0.02$).	Scarce literature.
Lemos 2023 [77]	Sixteen studies, 334 participants; single-arm meta-analysis.	Implant survival 92–100%; mean marginal bone loss 0.98 mm (95% CI 0.61–1.36).	Small studies of mixed design.
Awawdeh 2024 [74]	Thirty-five studies included from 923 screened.	Satisfaction rates 50–81%.	Heterogeneous instruments and populations.

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