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Retention Behavior and Surface Alterations of Ball and TRI Raptor Unsplinted Overdenture Attachments After Thermomechanical Aging: An In Vitro Study

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Research Article

Keywords: Dental Prosthesis, Implant-Supported, Dental Implants, Denture Retention, In Vitro Techniques, Microscopy, Electron, Scanning, Wear

Posted Date: June 10th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-9463831/v1

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Additional Declarations: No competing interests reported.

Version of Record: A version of this preprint was published at BMC Oral Health on September 5th, 2026. See the published version at https://doi.org/10.1186/s12903-026-09827-w.

Abstract

Background

To compare the time-dependent retentive-force behavior and wear-related surface alterations of two unsplinted overdenture attachment systems, a ball attachment system and a TRI Raptor Smart Box system, after standardized thermomechanical aging.

Methods

In this in vitro study, a ball attachment system (clear and gray matrix inserts) and a TRI Raptor Smart Box system (purple, clear and pink inserts) were evaluated (n = 10 per subgroup). Custom specimen holders were fabricated to simulate attachment–matrix engagement. Artificial aging was performed in a thermocycling chewing simulator between 5°C and 55°C with simultaneous cyclic loading. Retentive-force measurements were obtained after 120, 720, 1440 and 2160 cycles, corresponding approximately to 1, 6, 12 and 18 months of clinical use. Pull-off force was measured using a microtensile testing device. Representative components were examined by scanning electron microscopy after the final aging interval.

Results

Retentive force decreased significantly over time in all subgroups. In the ball attachment system, the gray insert consistently showed higher retentive-force values than the clear insert. In the TRI Raptor Smart Box system, the purple insert showed the highest retentive-force values at 1, 6 and 18 months, with a transient crossover at 12 months, when the clear insert showed the highest mean value. The pink Raptor insert showed the lowest values overall. SEM demonstrated subgroup-specific wear-related surface alterations after cyclic aging.

Conclusions

Retentive-force loss was not uniform across the tested unsplinted overdenture attachment subgroups. Insert-specific material and design characteristics influenced retention behavior and may be relevant to attachment selection and maintenance planning in implant overdenture therapy.

1. Background

Edentulism continues to impose a substantial functional and quality-of-life burden, particularly in older adults, despite a gradual decline in its global prevalence over recent decades [1]. Conventional complete dentures remain the most common treatment option for fully edentulous patients because of their relative simplicity and lower cost; however, their long-term clinical performance is frequently

compromised by insufficient retention, reduced masticatory efficiency, discomfort and variable patient adaptation [2]. These limitations are especially pronounced in the mandible, where dissatisfaction with denture retention and stability remains a common clinical problem [3].

Implant-retained overdentures have therefore become a well-established treatment option for the edentulous mandible. In particular, mandibular two-implant overdentures have been recognized as the first-choice standard of care for many edentulous patients because they offer a more predictable improvement in denture retention and function than conventional dentures [4]. In addition, systematic and multicenter clinical evidence has shown that implant-supported mandibular overdentures provide superior patient satisfaction and improved oral health-related quality of life compared with conventional complete dentures [5, 6]. Nevertheless, treatment success does not depend solely on implant survival; it is also closely related to the reliability of the attachment system connecting the prosthesis to the implants, which directly affects maintenance needs, ease of use and long-term functional performance [7].

Among unsplinted attachment systems, ball-type and locator-type attachments are the most widely used because they are clinically practical, relatively economical and compatible with routine mandibular overdenture therapy [8, 9]. However, retention provided by these systems is not constant over time. Both in vitro and clinical studies have shown that repeated insertion-removal cycles, functional loading and material wear may lead to progressive retention loss and increased prosthetic maintenance, with the magnitude of deterioration depending on attachment design and matrix material [8, 10, 11]. More recent systematic evidence comparing ball and locator systems has also emphasized that attachment selection influences not only retention and maintenance but also clinical and biomechanical performance, making the choice of attachment a relevant prosthetic variable rather than a purely technical preference [12].

Despite this growing body of evidence, literature remains concentrated on conventional ball, locator and bar systems, while comparative data on newer unsplinted attachment designs are still limited. In particular, there is a relative lack of studies evaluating contemporary attachment systems under combined thermomechanical aging conditions with repeated insertion-removal cycling and wear-oriented analysis. This limitation is clinically relevant because retention loss in overdenture therapy is largely associated with progressive matrix deterioration and maintenance frequency is closely related to the mechanical resilience of the attachment components [8, 11].

Therefore, the aim of the present in vitro study was to compare the retention behavior and wear-related changes of TRI ball and TRI Raptor unsplinted overdenture attachment systems after artificial aging.

2. Methods

2.1. Study design and experimental groups

This in vitro study was conducted at the Research and Development Laboratories of the Faculties of Dentistry at Istanbul Aydın University and Erciyes University, Turkey. The retentive-force behavior and wear-related surface changes of two unsplinted overdenture attachment systems were evaluated after cyclic aging. Two attachment systems from the same manufacturer (TRI Implant Swiss, Hünenberg, Switzerland) were investigated: a ball attachment system and a TRI Raptor Smart Box system. The ball attachment system comprised two matrix-insert subgroups based on insert color (clear and gray), whereas the TRI Raptor Smart Box system comprised three subgroups (purple, pink and clear). Each subgroup included 10 matrix inserts (n = 10).

2.2. Pilot testing and development of the experimental setup

A pilot phase was completed before the main experiment to verify the feasibility of the experimental setup. Initially, the attachment assemblies were mounted in a chewing simulator using a preliminary configuration intended to simulate maxillary and mandibular overdenture components. Because incompatibility was observed between the device and the attachment assemblies, custom holders were subsequently fabricated to allow stable mounting of the patrix and matrix components.

During pilot testing, retentive-force measurements were first attempted using a universal testing machine. However, because the retentive forces of the evaluated attachment systems were below the practical sensitivity range of that device for this application, all definitive pull-off measurements were performed with a microtensile testing device.

2.3. Fabrication of custom holders

Custom upper and lower holders were fabricated by a local manufacturer (Bilgin Motors, Istanbul, Turkey) using machined stainless-steel and aluminum rods. The lower holders were designed to simulate the implant-bearing mandibular component, whereas the upper holders were used to accommodate the matrix assemblies.

To simulate the supporting base, the holders were filled with autopolymerizing polymethyl methacrylate resin (PMMA; Imicryl, Konya, Turkey). After polymerization, standardized receptacles were prepared in the acrylic blocks to receive the implant analogs and the matrix housings. The receptacles were prepared so that the patrix and matrix components were aligned centrally and without intentional angulation.

2.4. Implant analogs and attachment assembly

A total of 20 implant analogs (diameter, 3.7 mm; length, 12 mm) were used in the study. The analogs were inserted into the prepared lower-holder blocks at bone level. Subsequently, 10 ball patrices and 10 TRI Raptor patrices were connected to the analogs using the manufacturer’s driver system and tightened with a torque wrench according to the manufacturer’s recommendation. All patrices were torqued to 25 N·cm.

Before incorporation of the matrix components, the undercut regions were isolated to prevent acrylic locking during polymerization. Petroleum jelly was applied between the upper and lower holder assemblies to prevent acrylic resin leakage and facilitate separation after processing. The matrix housings and retentive inserts were then incorporated into the opposing holders using autopolymerizing acrylic resin. Polymerization was completed in a pressure unit at 1000 psi until final setting.

2.5. Cyclic aging protocol

Artificial aging was performed using an 8-station chewing simulator with thermocycling capability (MOY-101, Moddental, Ankara, Turkey). The custom holder assemblies simulating the upper and lower components of an overdenture system were secured to the device and all specimens were checked individually before testing. The simulator was set to operate at 30 cycles/min. During cyclic aging, a standardized vertical seating load of 50 N was applied during insertion-removal cycling. This loading condition was selected to provide a controlled and reproducible laboratory challenge rather than to reproduce an exact patient-specific insertion force. Thermocycling was performed simultaneously during cyclic loading in distilled water between 5°C and 55°C, with a dwell time of 60 s and a transfer time of 10 s. Retentive-force measurements were obtained after 120, 720, 1440 and 2160 cycles, corresponding approximately to 1, 6, 12 and 18 months of clinical use, respectively, based on a commonly used laboratory assumption of approximately four insertion-removal events per day [13, 14].

2.6. Retentive-force measurement

Retentive-force measurements were performed using a microtensile testing device (MIC-100, Moddental, Ankara, Turkey) located at Istanbul Aydın University. For each test, the matrix and patrix components were aligned along the path of dislodgement and tensile separation was performed at a crosshead speed of 50 mm/min, consistent with previously reported in vitro overdenture attachment studies using comparable dislodgement rates [15, 16]. The maximum force required to disengage the matrix from the patrix was recorded in Newtons (N). Five consecutive pull-off measurements were obtained for each specimen at every evaluation interval and mean values were used for summary comparisons. The overall experimental setup for specimen assembly, cyclic aging and retentive-force testing is shown in Fig. 1.

2.7. Scanning electron microscopy evaluation

Following cyclic aging, representative matrix inserts and attachment components from the tested groups were examined by scanning electron microscopy (SEM) to qualitatively assess wear-related surface alterations after the 18-month evaluation. SEM imaging was performed using a GeminiSEM 500 system (ZEISS, Oberkochen, Germany). Attachment components were examined without coating, whereas retentive insert elements were sputter-coated with a 20-nm Au-Pd layer before imaging. Images were obtained at magnifications ranging from ×30 to ×250, depending on the specimen and region of interest.

2.8. Statistical analysis

All statistical analyses were performed using IBM SPSS Statistics for Windows, version 25.0 (IBM Corp., Armonk, NY, USA). Continuous variables were expressed as mean ± standard deviation or as median (first quartile–third quartile), according to data distribution. Normality was assessed using the Shapiro-Wilk test and homogeneity of variance was evaluated with the Levene test. For repeated-measures analyses, sphericity was assessed using Mauchly's test. When the sphericity assumption was met, sphericity-assumed results were reported; otherwise, the Huynh-Feldt correction was applied when epsilon was > 0.75 and the Greenhouse-Geisser correction was applied when epsilon was ≤ 0.75. Mixed-design repeated-measures analysis of variance (ANOVA) was used to evaluate the effects of subgroup and time. Three-way repeated-measures ANOVA was applied for analyses incorporating subgroup, time point, and repeated measurement number, whereas two-way repeated-measures ANOVA was used for subgroup comparisons across time. Multiple comparisons were performed using the Bonferroni-Dunn post hoc test. A P value < 0.05 was considered statistically significant.

2.8.1. Sample Size and Post-hoc Power Analysis

The sample size of n = 10 per subgroup was selected in accordance with comparable in vitro studies evaluating retentive-force behavior of overdenture attachment systems under cyclic aging conditions [15, 17, 18]. Previous laboratory studies have similarly used 10 specimens per test series and considered this sample size consistent with the existing in vitro literature, despite the absence of a universal consensus. Post-hoc power and sensitivity analyses were performed after data collection using Cohen's f as the effect size measure within ANOVA-based models, following the G*Power framework [19].

Observed means and standard deviations were used to calculate effect sizes for between-group comparisons using a one-way ANOVA model (k = 5 subgroups) and for within-group time effects using a one-way repeated-measures ANOVA model (m = 4 time points), with a two-tailed significance level of α = 0.05. For between-group comparisons, Cohen's f values ranged from 2.81 at 2160 cycles to 4.73 at 1440 cycles. For within-group time effects, Cohen's f values ranged from 4.32 in the Raptor-purple subgroup to 10.32 in the Raptor-clear subgroup. All observed effect sizes were substantially above the range conventionally interpreted as large in ANOVA-based power analysis. Achieved statistical power was 1.000 for all comparisons. Sensitivity analysis further indicated that the present sample size was capable of detecting effects with Cohen's f ≥ 0.52 for between-group comparisons and f ≥ 0.56 for within-group comparisons at 80% power, supporting the adequacy of n = 10 per subgroup for the analyses performed in this study.

3. Results

3.1. Time-dependent retentive force changes

Retentive force decreased significantly over time in both attachment systems (Table 1, Fig. 2). In the ball attachment system, the gray insert subgroup consistently showed higher retentive-force values than the clear subgroup, decreasing from 12.55 ± 0.21N to 2.93 ± 0.59N, whereas the clear subgroup decreased

from 11.58 ± 0.37N to 2.25 ± 0.42N. The time-dependent reduction was significant in both ball subgroups (both p = 0.001). In the TRI Raptor Smart Box system, significant time-dependent reductions were also observed in all three subgroups (all p = 0.001). The purple subgroup showed the highest retentive-force values at 120, 720, and 2160 cycles, whereas the clear subgroup showed the highest mean value at 1440 cycles. The pink subgroup showed the lowest retentive-force values overall.

Table 1
Time-dependent retentive force values within each subgroup (N)

Time	Ball-clear	Ball-gray	Raptor-purple	Raptor-clear	Raptor-pink
120 cycles	11.58 ± 0.37	12.55 ± 0.21	20.61 ± 2.10	16.42 ± 0.27	9.41 ± 0.61
720 cycles	8.25 ± 0.71	10.19 ± 0.43	13.94 ± 1.13	13.43 ± 0.78	7.58 ± 0.18
1440 cycles	5.34 ± 0.54	7.20 ± 0.55	9.06 ± 0.53	10.36 ± 0.38	4.45 ± 0.27
2160 cycles	2.25 ± 0.42	2.93 ± 0.59	5.84 ± 0.82	3.58 ± 0.16	1.67 ± 0.31

Note: Data are presented as mean ± standard deviation (N). Ball-clear and Ball-gray denote the clear and gray matrix inserts of the ball attachment system, respectively. Raptor-purple, Raptor-clear and Raptor-pink denote the purple, clear and pink matrix inserts of the TRI Raptor Smart Box system, respectively. Within-group time effects were significant for both ball subgroups and for all three Raptor subgroups (all p = 0.001).

3.2. Between-group comparisons at each evaluation interval

Significant between-group differences were observed at all evaluation intervals (Table 2). At 120 and 2160 cycles, the purple Raptor subgroup showed the highest retentive-force values, whereas the pink Raptor subgroup showed the lowest. At 720 cycles, the purple and clear Raptor subgroups showed similarly high values (13.94 ± 1.13N and 13.43 ± 0.78N, respectively), while the pink Raptor subgroup remained the lowest (7.58 ± 0.18N). The ball-gray subgroup showed an intermediate statistical profile at this interval, as it did not differ significantly from either the higher-retention Raptor subgroup pair or the lower-retention subgroup pair. At 1440 cycles, all five subgroups differed significantly from one another, with clear Raptor showing the highest retentive force (10.36 ± 0.38N) and pink Raptor the lowest (4.45 ± 0.27N) (p = 0.001).

Table 2
Between-group post hoc comparison of retentive force at each evaluation interval (N)

Time	Ball-clear	Ball-gray	Raptor-purple	Raptor-clear	Raptor-pink	p value
120 cycles	11.58 ± 0.37	12.55 ± 0.21	20.61 ± 2.10	16.42 ± 0.27	9.41 ± 0.61	p = 0.001
720 cycles	8.25 ± 0.71	10.19 ± 0.43	13.94 ± 1.13	13.43 ± 0.78	7.58 ± 0.18	p = 0.001
1440 cycles	5.34 ± 0.54	7.20 ± 0.55	9.06 ± 0.53	10.36 ± 0.38	4.45 ± 0.27	p = 0.001
2160 cycles	2.25 ± 0.42	2.93 ± 0.59	5.84 ± 0.82	3.58 ± 0.16	1.67 ± 0.31	p = 0.001

Data are presented as mean ± standard deviation (N). Within each row, values with different superscript lowercase letters indicate statistically significant differences between subgroups at the same evaluation interval according to post hoc multiple-comparison testing. Values sharing at least one superscript letter are not significantly different from one another. Accordingly, a value labeled “ab” does not differ significantly from values labeled either “a” or “b”. P values indicate the overall between-group comparison at each time point.

3.3. Scanning electron microscopy findings

Scanning electron microscopy (SEM) performed after 18 months of cyclic aging revealed qualitative surface alterations in all evaluated insert subgroups (Fig. 3). In the ball attachment system, both gray and clear inserts showed marginal irregularity, surface disruption and debris accumulation. The ball-gray insert demonstrated marked peripheral deformation, whereas the ball-clear insert showed intraluminal debris and fragmented surface material.

In the TRI Raptor Smart Box system, the clear and pink inserts generally maintained a more regular overall geometry at low magnification, although localized surface defects and marginal discontinuities were observed at higher magnification. The purple Raptor insert showed more obvious debris accumulation and irregular surface disruption. Taken together, the SEM images support the presence of wear-related surface changes after cyclic aging in both attachment systems.

4. Discussion

Mandibular implant overdentures remain a well-established treatment option for edentulous patients, and two-implant overdentures continue to be regarded as a benchmark treatment for the edentulous mandible in many clinical settings [4, 20]. Against that background, the present in vitro study compared the time-dependent retentive-force behavior of a ball attachment system and a TRI Raptor Smart Box system under standardized thermomechanical aging. Retentive force decreased in all subgroups over time, but the pattern and magnitude of reduction differed between inserts, indicating that matrix-specific material and design characteristics influence retention loss during cyclic aging.

This overall decline in retention is consistent with the literature on stud-type overdenture attachments, which shows that retentive performance is not static and that matrix replacement, retention loss, deformation and component wear are central to the long-term behavior of unsplinted attachment systems [9, 12, 21]. What the present study adds is a controlled comparison of subgroup-specific retentive-force changes within two contemporary unsplinted systems tested under identical aging conditions.

Within the ball attachment system, the gray insert outperformed the clear insert at every evaluation interval. This suggests that even within the same attachment design, color-coded inserts should not be assumed to behave identically over time. Previous work on ball attachments has similarly shown that retention loss is closely associated with progressive wear, deformation and surface alteration of retentive components. A study demonstrated that attachment wear influences overdenture retention [22] and later wear-simulation studies confirmed that stud attachments exhibit measurable retentive-force changes and surface damage after cyclic use [15, 17, 23]. The present results extend those observations by showing that subgroup-specific performance differences can persist throughout the full observation period in a ball attachment system.

The TRI Raptor Smart Box results were more differentiated. The purple insert showed the highest retentive-force values at 1, 6 and 18 months, whereas the clear insert showed the highest mean value at 12 months and the pink insert consistently demonstrated the lowest values. This nonuniform ranking suggests that initial retention and longer-term retention are not necessarily governed by the same material response. Comparative literature is dominated by ball, Locator, bar and magnetic systems rather than TRI Raptor-specific inserts, so direct one-to-one comparison is limited. Nevertheless, available in vitro evidence supports the broader principle that retention behavior is strongly affected by insert material, attachment geometry and the way wear accumulates during repeated insertion-removal cycles [18, 24–26]. In that respect, the present data provide useful subgroup-specific evidence for a system for which comparative published data remain limited.

One particularly noteworthy finding was the transient crossover observed at 12 months, when the clear Raptor insert exceeded the purple insert in mean retentive force despite the purple insert showing higher values at the other evaluation intervals. This pattern suggests that retention decline may not follow a strictly fixed material hierarchy throughout aging. A plausible explanation is that different insert materials or designs respond differently to thermocycling and repeated insertion-removal, with temporary differences in viscoelastic recovery, contact adaptation, deformation pattern or wear plateau behavior [27, 28]. Accordingly, the 12-month crossover observed in the present study may reflect a material-specific transitional phase rather than random variation alone.

The SEM findings support the interpretation that retention loss was wear-related. However, visible surface deterioration does not translate linearly into retentive-force reduction, because the location of damage, contact adaptation, and the geometry of the active retentive interface may be just as important as the overall extent of material alteration [17, 18, 22, 24]. In this respect, the SEM findings strengthen

the mechanical interpretation of the study, but they should not be read as a quantitative ranking of wear severity.

From a clinical perspective, these findings suggest that insert selection should not be based solely on attachment category or on retentive-force magnitude alone. Although the ball-gray insert and the purple Raptor insert showed the most favorable retentive profiles in the present dataset, greater in vitro retention should not automatically be interpreted as universally better clinical performance. Clinical attachment selection also depends on maintenance burden, patient dexterity, hygiene access, comfort, prosthesis insertion-removal tolerance and patient-reported outcomes [9, 12, 29]. In both systems, retention decreased progressively, with the magnitude of reduction becoming especially relevant by the later evaluation intervals. This supports the view that matrix replacement intervals should not be assumed to be identical across inserts, even within the same attachment family. The literature similarly indicates that thermal conditions, cleansing environment, repeated dislodgement, pH and long-term surface degradation may all influence the durability of overdenture attachments and shorten functional service life [18, 25, 26]. The present findings therefore may help refine preclinical expectations regarding maintenance planning, especially when stronger or weaker initial retention is intentionally selected.

The clinical meaning of late-cycle retention values should also be interpreted against previously proposed retention ranges. Although no single universal threshold applies to all overdenture systems, published data suggest that retention values above approximately 5 N may remain mechanically meaningful, whereas higher ranges may be preferable depending on attachment design and patient expectations [26, 30]. In the present study, several subgroups approached or fell below this level by the final evaluation interval, indicating that the observed late-stage differences may be clinically relevant from a maintenance perspective and not merely statistically significant. This reinforces the importance of interpreting retention values not only comparatively, but also in relation to whether they are likely to remain functionally useful over time.

Two further methodological considerations warrant brief discussion. First, the 50 N vertical seating load applied during insertion-removal cycling was selected to provide a controlled and reproducible laboratory challenge rather than to replicate an exact patient-specific finger force. Similar loading conditions have been used in overdenture-related in vitro studies to standardize experimental loading and evaluate prosthesis-attachment biomechanics under reproducible laboratory conditions [31, 32] and the present findings should therefore be interpreted accordingly, with the recognition that clinical insertion and removal forces may vary between patients and overdenture designs. Second, five consecutive pull-off measurements were performed at each evaluation interval to improve the reliability of individual force recordings. Repeated dislodgement protocols of this kind are well established in overdenture attachment research and are known to influence both retention and wear-related behavior over time [33, 34]. Although the measurement process itself constitutes a small amount of additional mechanical loading beyond the scheduled aging cycles, the same protocol was applied uniformly to all specimens and subgroups, standardizing this effect across conditions and making differential bias between groups

unlikely. Nevertheless, cumulative pull-off events should be recognized as part of the overall mechanical loading history of the specimens.

The findings should be interpreted in light of the study design. As an in vitro model, the present setup may not fully reproduce the multidirectional dislodging patterns, saliva chemistry, hygiene routines, dietary variability and patient-specific insertion-removal behavior encountered clinically. In particular, distilled water was used as the aging medium rather than simulated or natural saliva; salivary proteins, pH buffering and enzymatic activity may influence polymer degradation and surface wear in ways not captured by the present model, and this should be considered when translating the findings to clinical conditions [26, 27]. In addition, the data were generated under a single experimental configuration and within one system architecture; broader testing across different implant geometries, attachment designs and loading conditions would strengthen generalizability. Baseline retention values were available but were not included in the inferential comparisons; therefore, the present analysis reflects comparative retention behavior across scheduled follow-up intervals rather than full baseline-to-endpoint degradation trajectories. Another limitation is that the SEM assessment was qualitative and descriptive rather than quantitative. SEM was used in the present study to support interpretation of the mechanical findings by documenting wear-related surface alterations, debris accumulation, and material disruption after cyclic aging. However, no profilometric, roughness-based, or volumetric wear analysis was performed. As a result, the morphological findings cannot be correlated quantitatively with retentive-force loss, and the SEM observations should be interpreted as supportive rather than confirmatory evidence of wear severity [26, 35].

Despite these considerations, the study provides clinically relevant preclinical information. To our knowledge, detailed comparative data on TRI Raptor Smart Box insert subgroups under standardized thermomechanical aging remain limited and the present study offers a structured benchmark by combining retentive-force analysis with SEM-based surface characterization. Overall, these findings do not support the null hypothesis that retentive behavior remains unchanged over time or that no differences exist among the tested unsplinted attachment subgroups. Rather, they suggest that insert-specific material and design characteristics influence both retention loss and wear-related surface alterations. These in vitro data may serve as a useful preclinical basis for future prospective clinical studies evaluating matrix replacement frequency, patient-reported outcomes and long-term overdenture performance.

5. Conclusions

Retentive-force loss over time was not uniform across the tested unsplinted overdenture attachment subgroups. In the ball attachment system, the gray insert consistently outperformed the clear insert, whereas in the TRI Raptor Smart Box system the purple insert showed the most favorable overall retentive profile and the pink insert the weakest. SEM findings supported the mechanical results by demonstrating subgroup-specific wear-related surface alterations after cyclic aging. These findings indicate that insert-specific material and design characteristics influence retention behavior and may be

relevant to attachment selection and maintenance planning in implant overdenture therapy. The present data provide a preclinical basis for future clinical validation.

Abbreviations

ANOVA
Analysis of variance
Au-Pd
Gold-palladium
PMMA
Polymethyl methacrylate
SEM
Scanning electron microscopy

Declarations

Ethics approval and consent to participate: Not applicable. This in vitro study was conducted entirely on laboratory-fabricated specimens using implant analogs and attachment components, without the involvement of human participants, patient data, human tissue, or animals. The study adhered to international standards for in vitro dental research and reporting. Therefore, the Declaration of Helsinki was not applicable.

Clinical trial number: Not applicable.

Consent for publication: Not applicable.

Availability of data and materials: The data generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests: The authors declare that they have no competing interests.

Funding: The attachment systems and components used in this study were provided by TRI Implant Swiss (Hünenberg, Switzerland) as an in-kind material contribution. No financial support was received from the manufacturer or any other external source. The material provider had no role in study design, data collection, analysis, interpretation of findings or the decision to publish. The remaining study costs were covered by the authors.

Authors' contributions: H.K.: Conceptualization, methodology, supervision, writing - review and editing. E.S.: Investigation, formal analysis, visualization, data curation, writing - original draft preparation, writing - review and editing. Both authors read and approved the final manuscript.

Acknowledgements: The authors would like to thank the Research and Development Laboratories of the Faculties of Dentistry at Istanbul Aydın University and Erciyes University for providing the laboratory

infrastructure and technical support required for this study. The authors also thank Bilgin Motors, Istanbul, Turkey, for manufacturing the specialized sample holders used in the experimental setup.

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Figures

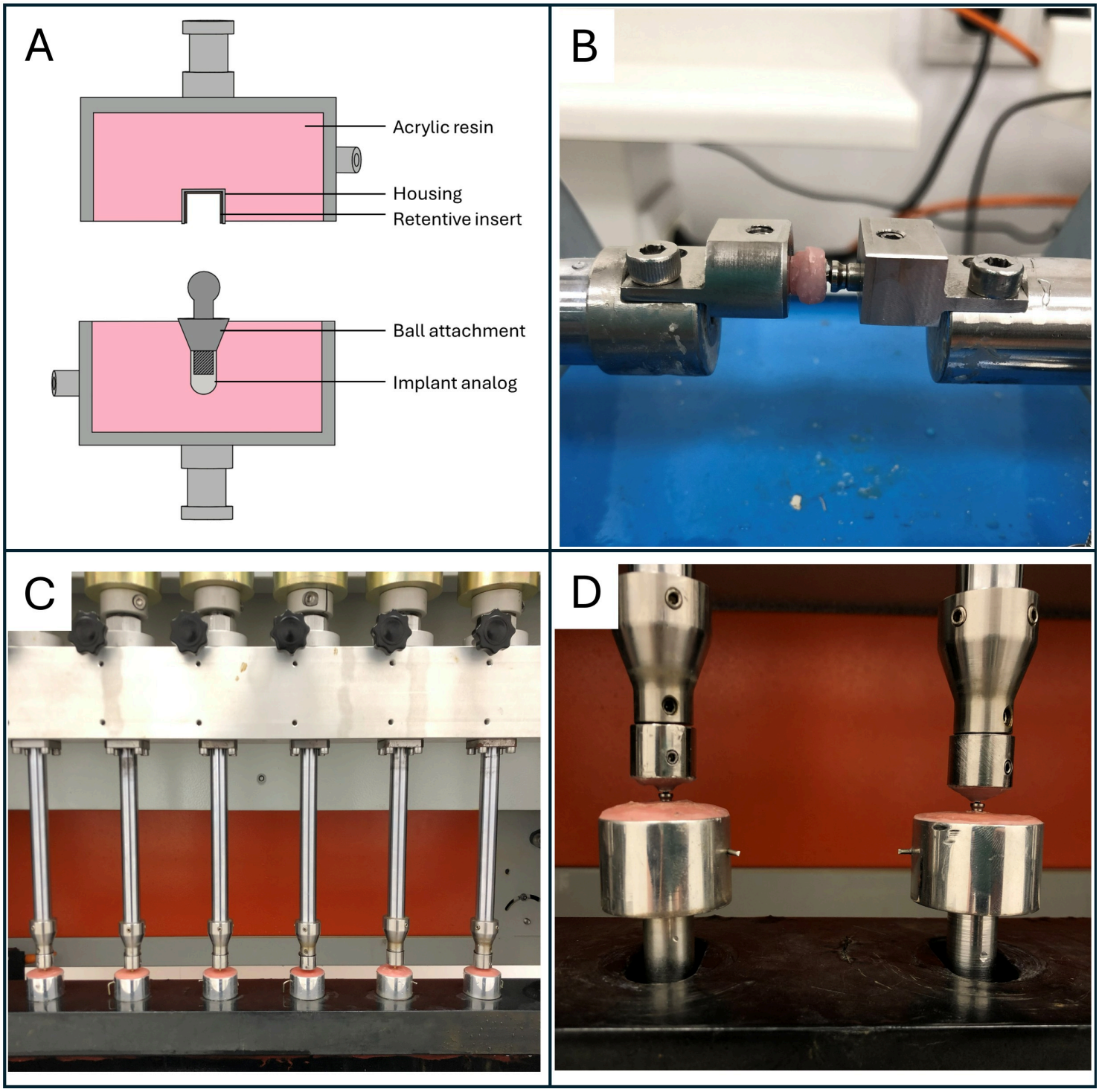


Figure 1

Experimental setup for cyclic aging and retentive-force testing. (A) Schematic cross-sectional representation of the custom specimen holder assembly. (B) Representative attachment-matrix connection within the custom holder. (C) Specimens mounted in the thermocycling chewing simulator during cyclic aging. (D) Retentive-force testing setup in the microtensile device.

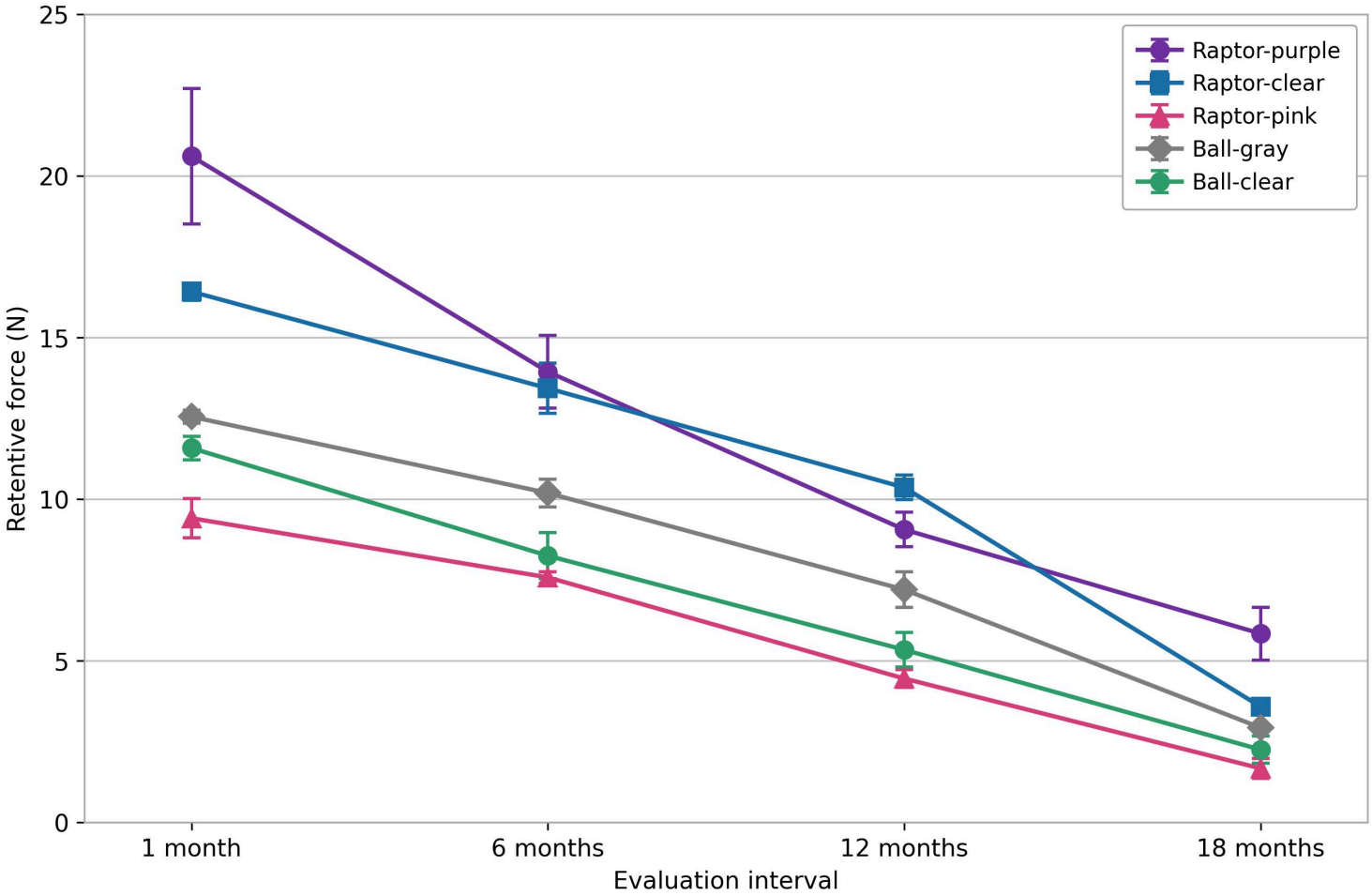


Figure 2

Time-dependent changes in retentive force across the evaluated attachment subgroups. Data are presented as mean ± standard deviation. Retentive force decreased progressively in all subgroups over the observation period. The gray ball insert consistently showed higher retentive-force values than the clear ball insert. A transient crossover was observed at 12 months, at which point the Raptor-clear insert exceeded the Raptor-purple insert.

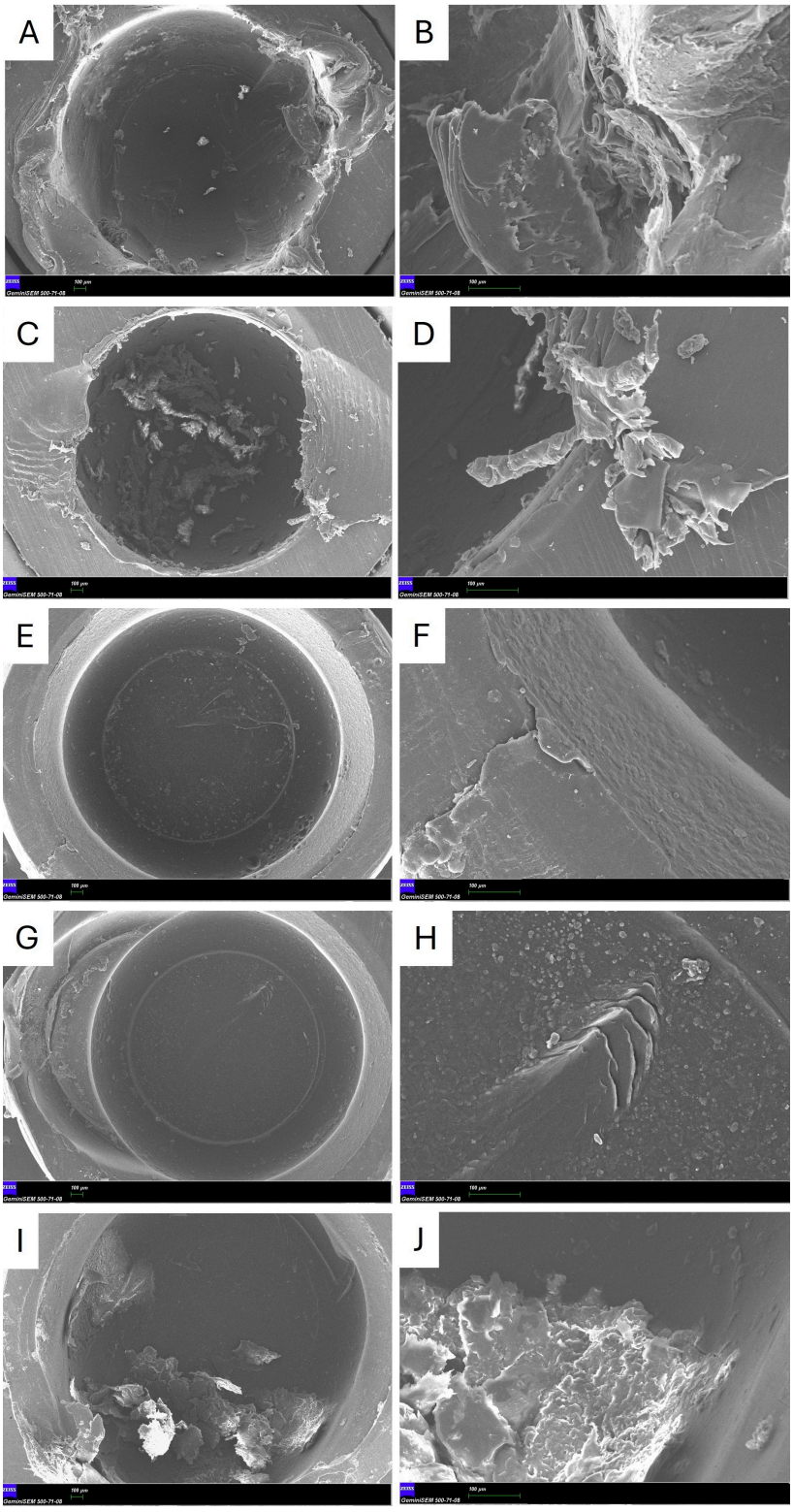


Figure 3

Representative scanning electron microscopy (SEM) images of the evaluated attachment inserts after 18 months of cyclic aging. Low-magnification images (×35) show the overall insert geometry and marginal contour, whereas high-magnification images (×150) demonstrate localized surface disruption, debris accumulation and material separation. (A, B) Ball-gray insert at low and high magnification, respectively. (C, D) Ball-clear insert at low and high magnification, respectively. (E, F) Raptor-clear insert

at low and high magnification, respectively. (G, H) Raptor-pink insert at low and high magnification, respectively. (I, J) Raptor-purple insert at low and high magnification, respectively.