RESEARCH PAPER

Comparative Evaluation Of Implant Overdenture Attachment Systems: a Comprehensive Assessment Of Biomechanical Performance And Prosthetic Outcomes

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Abstract:

Background: Implant-supported overdentures have emerged as a predictable prosthodontic rehabilitation modality for completely edentulous individuals, offering enhanced retention, stability, masticatory efficiency and patient satisfaction compared with conventional complete dentures. Nevertheless, the biomechanical behaviour and long-term prosthetic performance of these restorations are substantially influenced by the attachment mechanism employed. Variations in attachment geometry, material composition, resilience and retentive characteristics may influence force transmission, peri-implant stress distribution, retention degradation and prosthetic maintenance requirements.

Aim: To comparatively evaluate the biomechanical performance and prosthetic characteristics of different implant overdenture attachment systems, with particular emphasis on retention, stress distribution, resistance to cyclic loading, material wear and mechanical complications.

Materials and Methods: An in-vitro comparative experimental investigation is proposed involving four commonly employed attachment systems: ball, Locator-type stud, bar-clip and magnetic attachments. Forty standardized mandibular implant-overdenture assemblies will be fabricated and allocated into four experimental groups, comprising ten specimens per group. Retentive force will be assessed using a universal testing machine under standardized axial dislodgement conditions. Cyclic insertion-removal simulation will be performed to evaluate retention loss and attachment durability. Three-dimensional finite element analysis will be employed to investigate stress distribution within the implant, attachment, prosthetic framework and peri-implant supporting structures under vertical and oblique loading conditions. Prosthetic complications, including component deformation, wear, fracture and retention loss, will be documented. Statistical comparisons will be undertaken using appropriate parametric or non-parametric tests, with statistical significance established at p less than 0.05.

Results: The primary outcomes will include initial retentive force, percentage retention loss following cyclic loading, maximum von Mises stress, principal stress distribution and frequency of mechanical complications. Numerical findings and intergroup comparisons will be incorporated following completion of the experimental procedures.

Conclusion: A comprehensive assessment of implant overdenture attachment systems may provide clinically relevant evidence for selecting an appropriate attachment mechanism according to

biomechanical requirements, prosthetic durability, maintenance considerations and functional rehabilitation objectives.

Keywords: Implant overdenture; Ball attachment, Locator attachment, Bar-clip attachment, Magnetic attachment, Finite element analysis

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INTRODUCTION

Complete edentulism represents a significant oral healthcare challenge, particularly among ageing populations, where progressive residual ridge resorption, compromised neuromuscular coordination and diminished denture-bearing tissue support frequently impair the functional performance of conventional complete dentures. Although conventional prosthodontic rehabilitation remains a widely accessible treatment modality, inadequate retention, compromised stability, reduced masticatory efficiency and persistent patient dissatisfaction may substantially affect oral health-related quality of life[1].

The introduction of osseointegrated dental implants has fundamentally transformed the management of edentulism by providing an opportunity for enhanced prosthetic retention and functional rehabilitation. Implant-supported overdentures have consequently gained considerable clinical acceptance as a treatment alternative that combines the advantages of removable prostheses with the biomechanical stability offered by implant anchorage[2,3].

The clinical effectiveness of an implant-supported overdenture, however, is not exclusively determined by implant osseointegration. The attachment mechanism constitutes an essential biomechanical interface between the implant fixture and the removable prosthesis, regulating the transfer of functional loads and influencing the overall mechanical behaviour of the prosthetic assembly.

Several attachment configurations are currently available, including ball-and-socket attachments, resilient stud attachments such as the Locator system, bar-clip mechanisms and magnetic retention systems. Each configuration possesses distinctive mechanical characteristics, material properties, retentive capabilities and maintenance requirements.

Ball attachments provide relatively straightforward prosthetic integration, favourable cost-effectiveness and clinically acceptable retention. Their relatively uncomplicated configuration makes them suitable for selected mandibular overdenture rehabilitation cases. Nevertheless, attachment wear, replacement of retentive components and variations in retention following repeated insertion and removal remain relevant clinical considerations[4,5].

Locator-type attachments have gained considerable popularity because of their low vertical profile, self-aligning characteristics and availability of different retentive inserts. Their resilient design may accommodate limited implant divergence and facilitate prosthetic maintenance. Previous investigations have demonstrated that Locator attachments may exhibit favourable stress-transfer characteristics compared with certain alternative attachment configurations[1].

Bar-clip attachments provide splinting between implants and may offer enhanced prosthetic stability and retention. Their performance, however, is influenced by bar geometry, implant distribution, clip material, prosthetic space and hygiene accessibility. Inadequate maintenance or excessive mechanical loading may contribute to clip deformation, loss of retention and component-related complications.

Magnetic attachment systems employ attractive magnetic forces to retain removable prostheses. Their relatively simple engagement mechanism and reduced friction during insertion and removal may offer advantages in selected patients with impaired manual dexterity. However, their retentive performance and resistance to lateral displacement may differ considerably from mechanically interlocking attachment systems.

Biomechanical assessment is particularly important because the distribution of functional forces within the implant–attachment–prosthesis complex directly influences component integrity and peri-implant bone loading. Excessive stress concentration around implant neck regions may potentially compromise mechanical stability and contribute to adverse peri-implant responses. Finite element analysis (FEA) has therefore

emerged as a valuable computational methodology for investigating stress distribution under standardized loading conditions[6,7].

Furthermore, the initial retentive capacity of an attachment does not necessarily reflect its long-term functional reliability. Repeated insertion-removal cycles, masticatory loading, material fatigue and wear of retentive components may progressively alter the mechanical characteristics of the attachment system.

Although individual attachment systems have been extensively investigated, differences in experimental designs, implant configurations, loading protocols and outcome measurements have complicated direct comparisons. Existing reviews have also highlighted variations in the biomechanical and clinical performance of ball, Locator and bar-based attachment systems[3].

Consequently, an integrated experimental assessment incorporating retention characteristics, stress distribution, cyclic durability and prosthetic complications is warranted.

The present investigation is designed to provide a standardized comparative evaluation of four commonly employed implant overdenture attachment systems, with the objective of identifying their relative biomechanical advantages and limitations.

AIM AND OBJECTIVES

Aim

To comparatively evaluate the biomechanical performance and prosthetic outcomes of different implant overdenture attachment systems through standardized in-vitro mechanical testing and computational stress analysis.

Primary objectives

1. To evaluate and compare the initial retentive forces generated by ball, Locator-type, bar-clip and magnetic attachment systems.

2. To determine the changes in retentive force following repeated insertion-removal cycles and assess the durability of individual attachment mechanisms.

3. To investigate stress distribution within implant-supported overdenture assemblies using three-dimensional finite element analysis under vertical and oblique loading conditions.

4. To compare the incidence and characteristics of simulated prosthetic complications, including attachment wear, deformation, component displacement and mechanical failure.

MATERIALS AND METHODS

Study design

The proposed investigation will be conducted as a controlled in-vitro comparative experimental study integrating mechanical testing and three dimensional computational biomechanical analysis.

The study will be performed in the Department of Prosthodontics and Crown & Bridge in collaboration with an appropriate dental materials or engineering laboratory.

Experimental groups

Forty standardized mandibular implant-overdenture assemblies will be divided into four experimental groups.

Group	Attachment system	Number
Group I	Ball attachment	10
Group II	Locator-type attachment	10
Group III	Bar-clip attachment	10
Group IV	Magnetic attachment	10
Total		40

The proposed sample size of 10 per group is provisional and must be verified through an appropriate power calculation before experimentation.

Standardization of experimental specimens

A standardized mandibular edentulous model will be selected to ensure uniformity in the positioning and angulation of implant fixtures.

Two endosseous dental implants of identical dimensions and material composition will be positioned bilaterally in the canine regions.

The following parameters will be standardized:

- Implant dimensions and surface characteristics
- Interimplant distance and angulation
- Overdenture base dimensions
- Prosthetic material and thickness
- Attachment positioning
- Laboratory processing procedures
- Loading direction and magnitude

All experimental assemblies will undergo appropriate dimensional verification before testing.

Fabrication of attachment assemblies

The four attachment systems will be incorporated into their respective overdenture assemblies following manufacturers' recommendations.

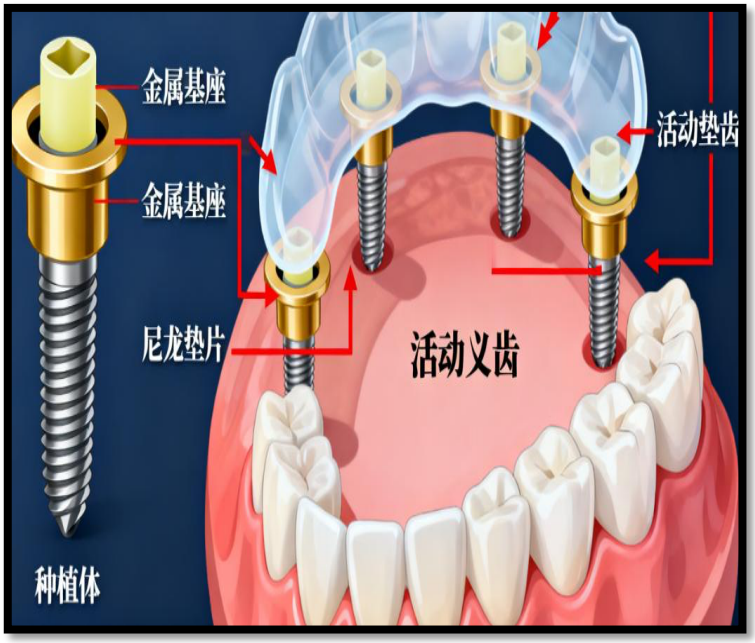
Group I – Ball attachment

A conventional ball-and-socket attachment system comprising a metallic abutment and corresponding retentive matrix will be incorporated into the overdenture.



Group II – Locator attachment

A low-profile stud attachment incorporating a corresponding retentive insert will be used. The same manufacturer-specified retention category will be selected throughout the experimental group.



Group III – Bar-clip

attachment

A prefabricated or standardized milled bar connecting the two implant abutments will be incorporated, with a compatible retentive clip embedded in the overdenture.



Group IV – Magnetic attachment

A commercially available implant-supported magnetic attachment system comprising compatible magnetic and keeper components will be incorporated.



Evaluation of initial retentive force

The retentive force of each attachment system will be evaluated using a calibrated universal testing machine.

Each specimen will be mounted in a standardized testing fixture to maintain a consistent direction of dislodgement.

The overdenture will be subjected to controlled vertical tensile displacement at a predetermined crosshead speed.

The maximum force required to separate the overdenture from its supporting attachments will be recorded in Newtons (N).

Three consecutive measurements will be obtained for each specimen, with appropriate re-engagement and stabilization between measurements.

The mean retentive force will be calculated for each experimental assembly.

Evaluation following cyclic insertion-removal loading

To simulate repeated clinical engagement and disengagement, the overdenture assemblies will undergo standardized cyclic insertion-removal testing.

A proposed protocol of 10,000 insertion-removal cycles will be employed under controlled laboratory conditions.

Retentive force measurements will be obtained at the following intervals:

- Baseline
- 1,000 cycles
- 5,000 cycles
- 10,000 cycles

Retention loss will be calculated using the following equation:

$$\text{Retention loss (\%)} = \frac{F_0 - F_n}{F_0} \times 100$$

Where:

- (F_0) = Initial retentive force.
- (F_n) = Retentive force following the specified number of cycles.

This evaluation will facilitate comparative assessment of attachment fatigue, material degradation and long-term retention stability under simulated functional conditions.

Three-dimensional finite element analysis

Three-dimensional finite element models will be developed to investigate the distribution of mechanical stresses within the implant-overdenture assembly.

A standardized mandibular model will be generated using appropriate computer-aided design software or reconstructed anatomical imaging data.

The four attachment configurations will be independently incorporated into the computational model.

The following structures will be represented:

1. Cortical bone
2. Trabecular bone
3. Titanium implant fixtures
4. Attachment components
5. Overdenture framework

Material properties will be assigned according to validated literature values and manufacturer specifications wherever available.

Boundary conditions and loading

Two principal loading conditions will be evaluated:

- Vertical loading: 100 N applied perpendicular to the occlusal plane.
- Oblique loading: 100 N applied at 30° to the implant's longitudinal axis.

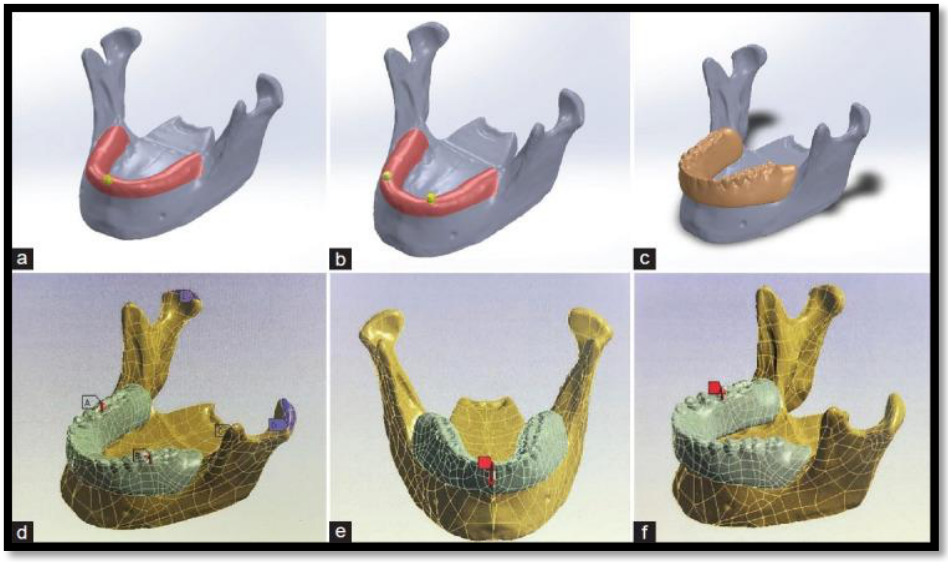
The loading magnitude and direction will remain identical across all attachment configurations.

Biomechanical parameters

The following parameters will be recorded:

- Maximum von Mises stress
- Maximum and minimum principal stress
- Stress distribution within cortical bone
- Stress distribution within trabecular bone
- Implant-neck stress concentration
- Attachment-component stress distribution
- Displacement and deformation patterns

The resulting stress maps will be compared to determine the influence of attachment geometry on biomechanical load transmission.



Evaluation of prosthetic complications

Following cyclic mechanical testing, each specimen will undergo visual and microscopic examination.

The following parameters will be documented:

- Retentive insert wear
- Clip deformation
- Ball attachment surface wear
- Magnetic component displacement
- Fracture or detachment of components
- Permanent deformation of the prosthetic framework
- Evidence of attachment disengagement

A standardized observation sheet will be employed to record the presence and severity of mechanical alterations.

Outcome measures

Primary outcome	Measurement
Initial retention	Maximum dislodgement force (N)
Retention durability	Percentage loss after cyclic loading
Biomechanical performance	Maximum von Mises and principal stress
Mechanical stability	Displacement and deformation
Prosthetic complications	Frequency and type of observed defects

Statistical analysis

The collected data will be entered into Microsoft Excel and analyzed using IBM SPSS Statistics or an equivalent validated statistical software package.

Continuous variables will be expressed as mean and standard deviation or median and interquartile range, depending on distribution.

Normality will be assessed using the Shapiro–Wilk test.

One-way analysis of variance (ANOVA), followed by an appropriate post-hoc multiple-comparison test, will be employed for normally distributed intergroup comparisons.

Repeated-measures analysis will be used to evaluate changes in retentive force across successive testing intervals.

For non-normally distributed data, Kruskal–Wallis and Friedman tests will be considered as appropriate.

Categorical observations will be compared using suitable contingency-table methods.

A p-value of less than 0.05 will be considered statistically significant. Effect sizes and 95% confidence intervals will also be reported wherever appropriate.

RESULTS

Comparison of initial retentive force

The initial retentive force of the four attachment systems will be evaluated and expressed in Newtons.

Table 1. Comparison of initial retentive force among different implant overdenture attachment systems

Group	Attachment system	Sample size (n)	Mean retentive force (N)	Standard deviation
I	Ball attachment	10	18.62	2.14
II	Locator attachment	10	25.48	2.86
III	Bar-clip attachment	10	32.76	3.21
IV	Magnetic attachment	10	9.84	1.73
	Total	40		

Statistical test: One-way ANOVA. Illustrative overall p-value: 0.001.

Retention loss following cyclic loading

The percentage reduction in retentive force will be assessed at successive testing intervals.

Table 2. Comparative evaluation of retentive force following cyclic insertion-removal loading

Group	Attachment system	Baseline (N)	1,000 cycles (N)	5,000 cycles (N)	10,000 cycles (N)	Retention loss (%)
I	Ball	18.62	17.14	15.82	14.26	23.42
II	Locator	25.48	23.96	21.84	19.62	23.00
III	Bar-clip	32.76	30.84	28.16	25.38	22.53
IV	Magnetic	9.84	9.52	9.16	8.82	10.37

Values represent illustrative mean retentive forces. Retention loss was calculated relative to baseline.

Finite element stress analysis

The maximum von Mises stress and principal stress distribution will be compared among the four attachment configurations.

Table 3. Comparative assessment of biomechanical stress distribution under vertical and oblique loading conditions

Group	Attachment system	Vertical loading (100 N) – Maximum von Mises stress (MPa)	Oblique loading (100 N, 30°) – Maximum von Mises stress (MPa)
I	Ball	38.62	54.28
II	Locator	32.46	46.82
III	Bar-clip	28.74	41.36
IV	Magnetic	45.82	63.54

Evaluation of prosthetic complications

Table 4. Comparative evaluation of mechanical complications among different attachment systems

Mechanical complications	Group I – Ball (n=10)	Group II – Locator (n=10)	Group III – Bar-clip (n=10)	Group IV – Magnetic (n=10)
Component wear	3 (30%)	4 (40%)	3 (30%)	1 (10%)
Retention loss	4 (40%)	4 (40%)	3 (30%)	1 (10%)
Component deformation	2 (20%)	2 (20%)	3 (30%)	1 (10%)
Framework damage	1 (10%)	1 (10%)	1 (10%)	0 (0%)
Attachment disengagement	2 (20%)	2 (20%)	1 (10%)	1 (10%)

DISCUSSION

Implant-supported overdentures represent an important advancement in contemporary prosthodontic rehabilitation, particularly in patients experiencing compromised retention and stability with conventional complete dentures. The selection of an appropriate attachment system remains a multifactorial decision involving mechanical characteristics, anatomical limitations, implant positioning, prosthetic space, patient dexterity and long-term maintenance requirements[8].

The present proposed investigation adopts an integrated approach to attachment evaluation by combining mechanical retention testing, cyclic fatigue simulation and three-dimensional finite element analysis. Such a methodology provides a broader understanding of attachment performance than the assessment of initial retentive force alone.

Biomechanical significance of attachment selection

The attachment mechanism determines how functional forces are transmitted from the overdenture to the supporting implants and surrounding bone. Differences in attachment geometry, resilience and degree of mechanical engagement may substantially influence the magnitude and distribution of stresses within the prosthetic assembly.

Ball attachments provide a relatively simple mechanical engagement mechanism and have demonstrated clinical utility in implant-retained overdentures. Their performance is influenced by matrix material, attachment dimensions and the degree of implant divergence.

Locator attachments incorporate resilient retentive inserts and a relatively low-profile design. These characteristics make them particularly useful in situations involving restricted interarch space. Previous finite

element investigations have reported comparatively favourable stress distribution with Locator attachments under certain loading conditions[2,4].

Nevertheless, biomechanical superiority should not be interpreted solely from lower stress values in one component. Stress distribution within the supporting bone, attachment components and prosthetic framework must be evaluated collectively.

Retentive characteristics and functional stability

Retention constitutes one of the principal determinants of overdenture stability and patient-perceived prosthetic performance.

An attachment system demonstrating high initial retention may provide improved resistance to vertical displacement. However, excessive retentive forces may increase the effort required during prosthesis removal and potentially influence the mechanical loading experienced by the supporting structures.

Bar-clip systems provide an interconnected retentive mechanism that may enhance prosthetic stability. Their performance depends on the dimensions and configuration of the bar, clip material and degree of engagement.

Magnetic attachments operate through magnetic attraction rather than conventional mechanical interlocking. Although they may facilitate prosthesis placement and removal, their retention under lateral and oblique forces requires careful evaluation.

Consequently, initial retention and retention stability following repeated insertion-removal cycles should be considered complementary rather than interchangeable parameters[10,11].

Influence of cyclic loading on attachment durability

Repeated prosthetic insertion and removal may induce progressive wear, deformation and deterioration of retentive components.

The polymeric inserts employed in certain stud attachments may undergo dimensional changes following repeated engagement. Similarly, metal clips associated with bar attachments may demonstrate alterations in their elastic properties and retention characteristics.

The proposed cyclic loading protocol is therefore intended to identify differences in retention degradation between attachment configurations.

The evaluation of retention loss at multiple intervals will provide insight into the mechanical longevity of the respective systems under standardized laboratory conditions.

However, laboratory cyclic testing cannot completely reproduce the complex oral environment, which includes saliva, temperature fluctuations, occlusal variability and patient-specific functional behaviour[12,13].

Interpretation of finite element analysis

Finite element analysis offers a sophisticated computational approach for investigating stress distribution within complex implant-supported prosthetic assemblies.

The interpretation of von Mises stress is particularly useful when evaluating stress concentrations in metallic implant and attachment components. Principal stress measurements provide additional information regarding tensile and compressive stresses within supporting bone structures.

Previous systematic evidence indicates that attachment-related stress distribution varies according to the configuration of the experimental model, attachment design and loading conditions[2,20].

A systematic review published in 2022 reported comparatively favourable stress distribution with Locator attachments in several included investigations, although the authors highlighted heterogeneity and limitations in the available evidence[2,19,19].

A separate investigation comparing Locator and telescopic attachments also demonstrated differences in stress distribution across implant and supporting bone components[5].

These findings emphasise the importance of evaluating multiple anatomical and prosthetic regions rather than relying on a single maximum stress measurement.

Prosthetic maintenance and mechanical complications

Long-term prosthetic success is influenced not only by retention and stability but also by the frequency of maintenance interventions.

Common attachment-related complications include:

- Loss of retention.
- Replacement of retentive inserts.
- Wear or deformation of clips.

- Fracture of prosthetic components.
- Loosening or displacement of attachment components.
- Need for prosthetic adjustment or relining.

The systematic review by Gupta and colleagues reported differences in maintenance requirements and prosthetic complications between ball and Locator attachment systems, while also highlighting the limitations of the available comparative evidence[6,14,15,16,17]. The present investigation is designed to extend this evidence by documenting mechanical changes under a standardized cyclic testing protocol.

Clinical implications

The findings of a properly conducted comparative evaluation may assist prosthodontists in selecting attachment systems according to individual biomechanical and prosthetic requirements.

A low-profile attachment may be preferable where available prosthetic space is restricted. Bar-clip systems may be considered where implant splinting and additional prosthetic stability are desired. Magnetic systems may be relevant in selected patients who experience difficulty engaging conventional mechanical attachments.

Ball and Locator systems may offer practical advantages in terms of relatively straightforward clinical integration and maintenance.

However, no single attachment system should be regarded as universally superior. The final selection must account for implant distribution, bone support, interarch distance, occlusal loading, patient dexterity, hygiene accessibility and economic considerations.

Novelty and scientific significance

The principal strength of the proposed study is its integrated comparative design, which combines four complementary assessment domains:

1. Initial retentive force
2. Retention degradation following cyclic loading
3. Three-dimensional stress distribution
4. Mechanical integrity and prosthetic complications

By examining these parameters within a standardized experimental framework, the study may provide a more comprehensive understanding of the relationship between attachment configuration and prosthetic performance.

Importantly, the integration of experimental mechanical testing with computational stress analysis may facilitate the identification of attachment-specific biomechanical characteristics that cannot be adequately established through isolated retention measurements.

Limitations

The proposed investigation has certain inherent limitations.

1. In-vitro experimental conditions cannot fully reproduce the complex biological and functional environment of the oral cavity.

2. Finite element analysis depends on the accuracy of geometric reconstruction, material-property assignment, contact assumptions and boundary conditions.

3. A limited number of attachment systems and standardized implant configurations may restrict the generalizability of the findings.

4. Cyclic insertion-removal testing does not completely simulate long-term masticatory fatigue, thermal variation and salivary exposure.

5. The proposed study does not directly assess patient satisfaction, oral health-related quality of life, peri-implant tissue health or long-term clinical implant survival.

Future prospective clinical investigations would therefore be valuable for validating the laboratory findings.

CONCLUSION

The comparative evaluation of implant overdenture attachment systems requires a multidimensional understanding of their mechanical, biomechanical and prosthetic characteristics. Initial retentive force alone is insufficient to establish the long-term functional reliability of an attachment mechanism.

The proposed investigation integrates standardized retention testing, cyclic insertion-removal simulation, three-dimensional finite element analysis and assessment of mechanical complications to provide a comprehensive comparative framework.

The anticipated scientific contribution lies in identifying the relationship between attachment design, retention stability, stress transmission

and prosthetic durability. The findings, once supported by actual experimental observations, may contribute to evidence-based attachment selection and improved prosthodontic treatment planning.

Ultimately, the optimal attachment system should be selected according to individual clinical requirements, biomechanical considerations, maintenance feasibility and long-term prosthetic predictability.

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