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Comparative Evaluation of Screw Loosening in Zirconia Restorations with Different Abutment Designs

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Abstract

Background: Screw loosening is considered a leading mechanical complication in implant-supported restorations. Hybrid abutments, combining a titanium base with a ceramic mesostructured, were proposed to enhance stability and esthetics. **Objective:** We aimed to evaluate screw-loosening behavior in implant-supported zirconia restorations fabricated with various abutment designs. **Methods:** Thirty-six implant analogs were divided into three groups: (A) a one-piece hybrid abutment crown, (B) a two-piece hybrid zirconia abutment with a separated crown, (C) and a stock abutment with zirconia crown. Restorations were fabricated with CAD/CAM, bonded using a dual cure resin cement, and torqued to 35 Ncm to the analogs. The initial removal torque (RTV1) was measured, followed by thermal cycling and mechanical loading (500 cycles, 120,000 load cycles). The post-aging removal torque (RTV2) was measured and the torque loss percentage was calculated. Paired *t*-tests, ANOVA, and Tukey's test were used ($p < 0.05$). **Results:** All groups demonstrated significant torque loss following aging ($p < 0.001$). Group A showed the highest torque loss (12.0%), while Groups B and C exhibited lower loss (7.6% and 7.9%, respectively). The between-group difference was statistically significant ($p < 0.001$), except for between Groups B and C ($p = 0.53$). **Conclusions:** Within the limitations of this in vitro study, the abutment configuration affected screw preload stability. The one-piece hybrid abutment crown showed greater torque loss after aging, while the two-piece and stock abutment designs maintained comparatively better stability. Further clinical studies are required to confirm these findings.

Keywords: screw loosening; hybrid abutment; zirconia; dental implants; implant-supported restoration

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1. Introduction

Implants are generally considered a predictable and effective method for managing tooth loss, with single implant-supported crowns demonstrating survival rates exceeding 90% after five years of follow-up [1,2]. Nevertheless, the question of which abutment design provides the best balance between load-bearing capacity and esthetic outcomes is still debated [3].

Titanium abutments remain the conventional reference standard due to their high durability and extended period of clinical success [3,4]. However, in patients with a thin gingival biotype, they may induce a bluish-gray change in the surrounding implant mucosa. Although subgingivally placing the restoration margin can reduce this effect, it increases the risk of cement-related complications [3,4].

With advances in ceramics and CAD/CAM technology, alternative solutions such as all-ceramic abutments have been introduced to improve esthetics [5]. Zirconia abutments, in particular, provide a natural appearance but are less accurate than titanium, often showing wider marginal gaps and different mechanical properties such as hardness and elasticity that may compromise stability [6–8].

To overcome these drawbacks, hybrid abutments were developed, combining a titanium insert with a ceramic mesostructure. This configuration offers the mechanical strength of titanium while preserving the favorable esthetics of ceramics, and it has been reported to improve biomechanical stability and minimize clinical issues such as cervical fractures or soft-tissue complications [9,10]. Hybrid abutments can be manufactured either as a one-piece design, in which the crown and abutment are milled together and bonded to a Ti-base, or as a two-piece restoration, where the customized zirconia abutment is bonded first and the crown is cemented afterwards [11–14].

Despite these advances, screw loosening represents a major mechanical issue observed in implant restorations, with a reported rate of incidence ranging from 5.6% to 12.7% within five years [15,16]. This complication may compromise implant stability and contribute to biological problems such as marginal bone loss or peri-implantitis [17]. Multiple factors play a role in screw loosening, including micromovement at the implant–abutment interface, preload loss, settling effects, and improper torque application; moreover, the biological conditions in the oral cavity may influence screw joint stability, and the contamination of the implant–abutment interface with saliva or blood has been reported to interfere with preload and reduce reverse torque values, whereas maintaining a clean interface improves joint stability [17]. Among the different evaluation methods, measurement of removal torque is considered the most reliable and widely used technique [18].

Previous research has predominantly examined factors such as abutment height, angulation, and retention mechanisms [15–18]. However, fewer studies have directly compared different zirconia-based abutment configurations under standardized aging conditions. Therefore, this study provides a comparative in vitro evaluation of screw loosening behavior among one-piece hybrid abutment crowns, two-piece hybrid zirconia abutments, and stock titanium abutments.

Therefore, the null hypothesis of this study was that there would be no significant difference in removal torque loss among the three abutment designs tested.

2. Materials and Methods

2.1. Study Design and Sample Size

For thirty-six implant analogs (MegaGenImplant Co., Ltd., Daegu, Republic of Korea; Diameter: 4 mm; Length: 12 mm), the sample size was determined using G*Power software (version 3.1.9.7), assuming an effect size of 0.40, an α of 0.05, and a statistical power of 0.80.

2.2. Sample Mounting

The analogs were mounted in 3D-printed PMMA blocks, Dentium Co., Ltd., Seoul, Republic of Korea (20 $\times$ 20 $\times$ 25) using autopolymerizing acrylic resin, and the implant analogs were positioned perpendicular to the occlusal surface of the PMMA blocks using a dental surveyor to ensure standardized vertical alignment All molding and specimen preparation procedures were performed by a single trained operator to ensure consistency in technique and to minimize operator-related variability.

2.3. Scanning the Samples

A digital scan of each PMMA block containing the implant analog was performed using an extra-oral desktop scanner (Medit T710, Medit Crop., Seoul, Republic of Korea).

An HD + HD resolution was used to accurately record the implant platform position. This scan acted as the reference model for designing the zirconia restorations in all groups, ensuring standardized crown morphology and consistent seating across the different abutment configurations. The obtained STL files were saved and imported into CAD software (ExoCAD, DentalCAD Galway 3.0,GmbH, Darmstadt, Germany) for processing [19].

2.4. Sample Preparation

Samples were distributed into three groups (n = 12), namely Group A (one-piece hybrid abutment crown), Group B (two-piece custom hybrid zirconia abutment + crown), and Group C (stock titanium abutment + zirconia crown), as shown in Table 1 and in Figure 1.

Table 1. An overview of the three abutment configurations.

Group	Name of Abutment	Restoration Configuration	Type
A	Hybrid Abutment Crown	One-Piece Zirconia Crown And Abutment Milled As A Single Monolithic Unit And Bonded To A Ti-Base	Screw-Retained
B	Hybrid Abutment	Two-Piece Hybrid Zirconia Abutment + Crown; Custom Zirconia Abutment Bonded To A Ti-Base; Zirconia Crown Cemented Separately	Screw-Retained
C	Stock Titanium Abutment	Prefabricated Titanium Abutment With CAD/CAM Zirconia Crown	Screw-Retained

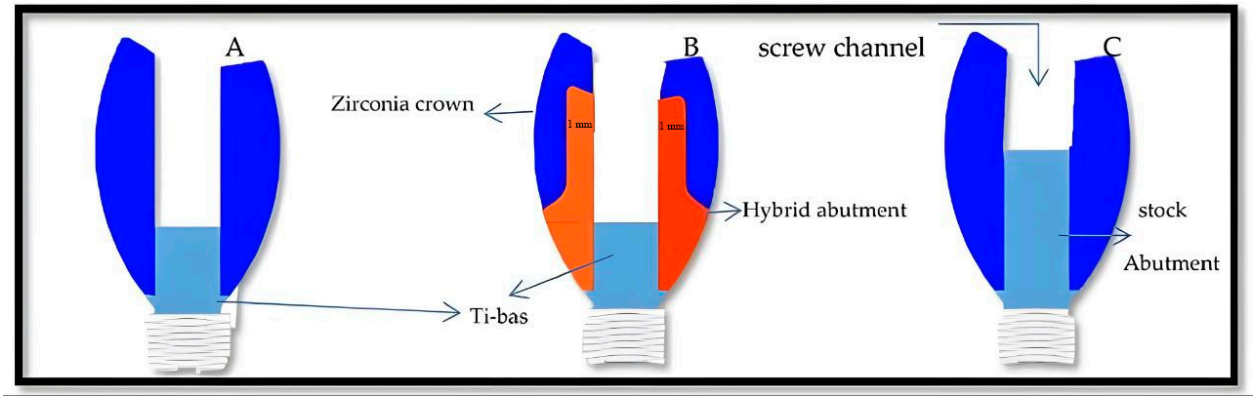


Figure 1. A schematic cross-sectional representation of the three abutment configurations tested. Group (**A**): One-piece hybrid abutment crown bonded to a Ti-base. Group (**B**): Two-piece hybrid zirconia abutment with a separate crown. Group (**C**): Stock titanium abutment with a zirconia crown.

2.5. Parameters of the Crown

For the zirconia maxillary right first premolar, a 40 µm cement gap (which was determined Via a pilot study), measuring 11.5 mm (length) by 8.5 mm (width) [20,21], and a linear screw-channel originating from the center of the occluding surface were used. Using the same STL file and uniform cement spacing helped to reduce variability.

2.6. Fabrication of Restorations

Group A: The selection of the Ti-base was made through the (CAD software, Galway 3.0 exocad GmbH, Darmstadt, Germany) library, in accordance with the implant system specifications, namely MEGA GEN–ANY RIDGE (MegaGen Implant Co., Ltd., Daegu,

Republic of Korea), with dimensions of 4 mm (diameter) 4.5 mm (length), as depicted in Figure 2. Subsequently, the hybrid abutment crown was virtually modeled over the Ti-base.

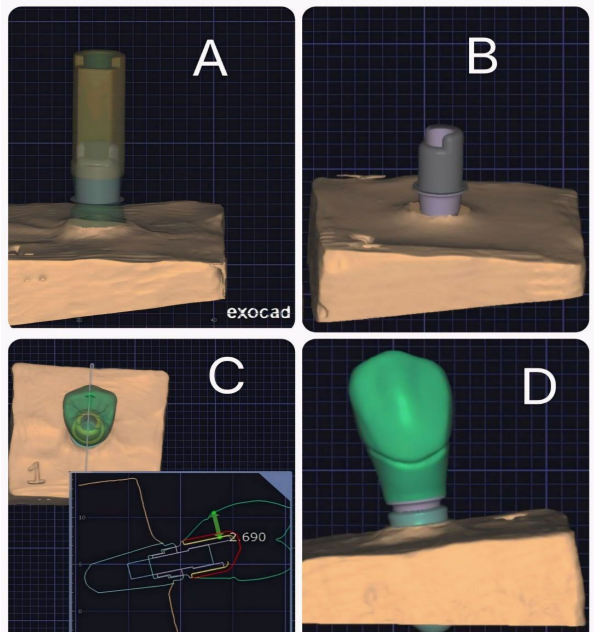


Figure 2. Fabrication of one-piece restoration: scan body on STL file (**A**), selection of Ti-base from library (**B**), and hybrid abutment crown cross-section (**C**) after completing design (**D**). The different colors shown in the images represent the default Exocad visualization for distinguishing components.

Group B: After selecting the same Ti-base as used in Group A, the custom abutment (L:7) design was designed over the selected Ti-base and then the crown was designed to cover over that.

Group C: A prefabricated stock abutment (Diameter: 4 mm; Length: 7 mm; ANY RIDGE system, MEGAGEN, Implant Co., Ltd., Daegu, Republic of Korea) was selected from the library and the zirconia crown was digitally designed to fit this abutment. This configuration represented a screw-retained zirconia restoration supported on a stock titanium abutment, and the crown abutment was secured to the implant analog using the abutment screw.

With all models standardized to maintain identical morphological and structural features upon completion, the completed design was exported in STL format and transferred to CAM (Computer-Aided Manufacturing) software for subsequent fabrication. Moreover, CAD/CAM fabrication provided a high level of precision across all groups.

After milling, specimens were polished and glazed, since surface defects are known to initiate cracks and lower fracture resistance. Previous studies also suggest that glazing can seal micro-defects and even support partial crack healing [22,23].

2.7. Surface Treatment

Ti-bases, abutments, and intaglio crown surfaces were airborne-particle-abraded using 50 μm of Al_2O_3 particles (BEGO easy blast, Bremen, Germany) at a pressure of 2 bars from a distance of 5 mm for 15 s. Subsequently, the specimens were cleaned using an ultrasonic cleaner with a 97% isopropanol solution for 3 min, after which they were dried. Thereafter, the specimens underwent treatment with a universal primer (Monobond Plus, Ivoclar Vivadent, Schaan, Liechtenstein). The primer was meticulously applied to the Ti-bases and titanium abutments for 20 s, followed by a reaction period of 60 s. A gentle airflow was employed to facilitate the drying of these samples.

2.8. Cementation Protocol

All restorations were bonded using dual-cure self-adhesive resin cement (RelyX U200, 3M ESPE, Seefeld, Germany).

The cementation steps differed by group: A one-step process was followed for Group A, with the hybrid abutment crowns being bonded to the Ti-base using dual-cure self-adhesive resin cement.

For Group B (two-piece hybrid abutment with separate crown), the zirconia abutment was first bonded to the Ti-base extraorally. A dual-cure self-adhesive resin cement (RelyX U200) was applied, and the abutment was seated onto the Ti-base, followed by a short tack-light to stabilize the set, and then full light-curing for approximately 20 s per surface by Drs Light AT (Good Doctors Co., Ltd., Seoul, Republic of Korea; intensity: 1200 mW/cm^2), as shown in Figure 3.

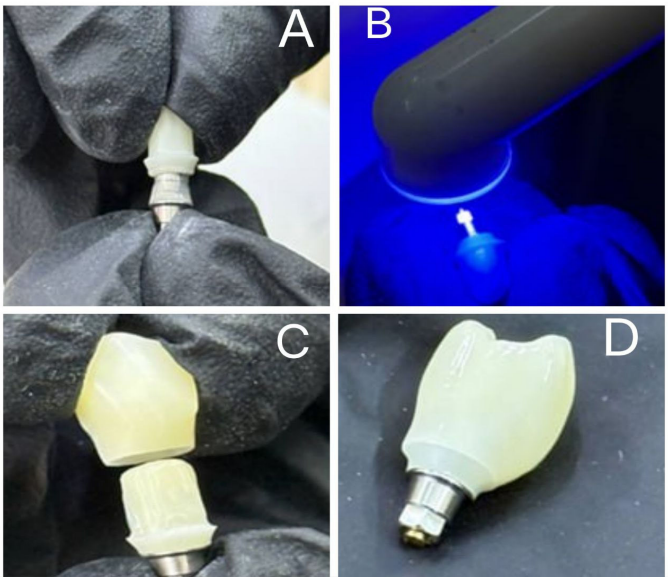


Figure 3. The cementation of the two-piece design (Group B) using resin cement rely X U200. The cementation of the custom-made zirconia abutment to the Ti-base after applying cement on the intaglio surface: (**A**); light curing: (**B**); the cementation of the crown to the custom abutment: (**C**); the restoration after the completion of cementation: (**D**).

To ensure correct alignment, seating was guided by the anti-rotational internal connection of the Ti-base, along with the digital reference scan, which preserved the intended orientation of the abutment. The zirconia crown (with screw channel) was then cemented onto the bonded abutment.

The choice of a self-adhesive resin cement was intended to reduce technique sensitivity and provide reliable stress distribution. This cement eliminated multiple bonding steps while still ensuring adequate retention [24].

In Group C, cementation was carried out between the stock abutment and the zirconia crown. For restorations, in all groups, the screw channel openings were occluded with Teflon tape to avoid cement blockage. The cement was placed on the intaglio surface, and the restorations were seated by applying gentle finger pressure; the remaining cement was gently removed using a micro-brush, and light curing was subsequently carried out for 20 s per surface from all aspects of the crown via Drs Light AT (Good Doctors Co., Ltd., Seoul, Republic of Korea; intensity: 1200 mW/cm^2) to strengthen polymerization, in line with studies indicating that dual-cured cements with sufficient light exposure display better mechanical performance. A constant load of 5 kg was applied during cementation to standardize cement film thickness [25].

2.9. Measurement of Preloading Removal Torque (RTV1)

Restorations were torqued to 35 Ncm by utilizing the screwdriver from the manufacturer along with a digital torque meter LUTRON TQ-8800, Lutron Electronic Enterprise Co., Ltd., Taipei, Taiwan; accuracy of ±1.5%. The torque device was factory-calibrated, and as it is a new device, this study represents its first use, as shown in Figure 4C. The specimens were stabilized using a metallic mold to firmly hold them in position and prevent any movement during testing, as shown in Figure 4A. Torque measurements were obtained digitally, which reduced operator variability and increased the reliability of the results [18]. A new abutment screw was used for each specimen to eliminate the effects of wear and metal fatigue associated with repeated tightening. We retightened the screw after 10 min after initial torque, and this step was included as part of the protocol as earlier studies suggest that it compensates for the settling effect and helps to preserve preload stability [26,27]. After another 10 min, the removal torque was recorded by applying a counter-clockwise force using the torque wrench as in Figure 4B. The maximum value obtained was defined as the Preload Removal Torque Value (RTV1) [28,29]. Both tightening and retightening were carried out according to the same protocol. Access holes were sealed with PTFE tape (Teflon) placed 2 mm apical to the occlusal plane, then filled with composite resin Filtek Z350 XT; 3M ESPE, St. Paul, MN, USA, and exposed to light curing for 40 s by Drs Light AT, Good Doctors Co., Ltd., Seoul, Republic of Korea; intensity: 1200 mW/cm^2, as shown in Figure 5.

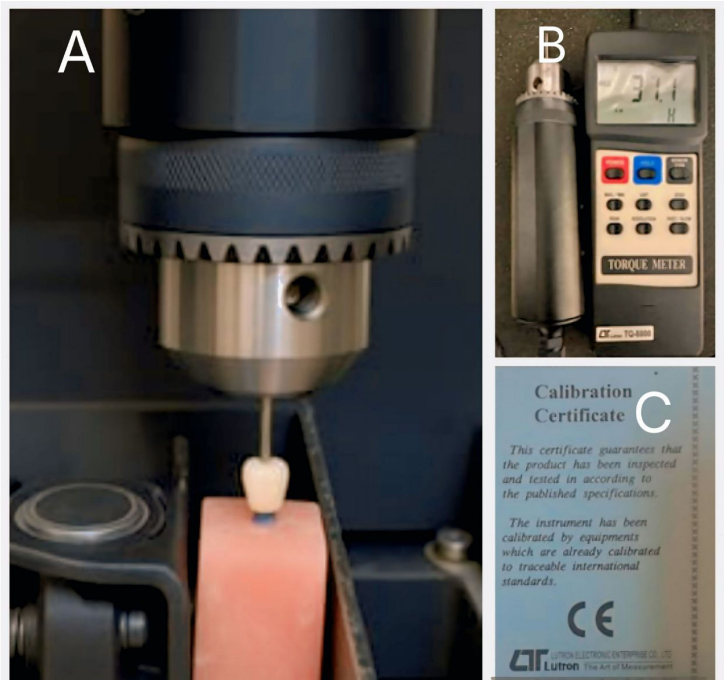


Figure 4. Preloading measurement using a calibrated digital torque wrench after initial tightening: the specimen was fixed in a metallic mold to ensure stability during testing: (**A**); measuring the preloading removal torque value after 10 min: (**B**); the Calibration Certificate of the torque meter (Lutron Electronic Enterprise Co., Ltd., Taipei, Taiwan): (**C**).

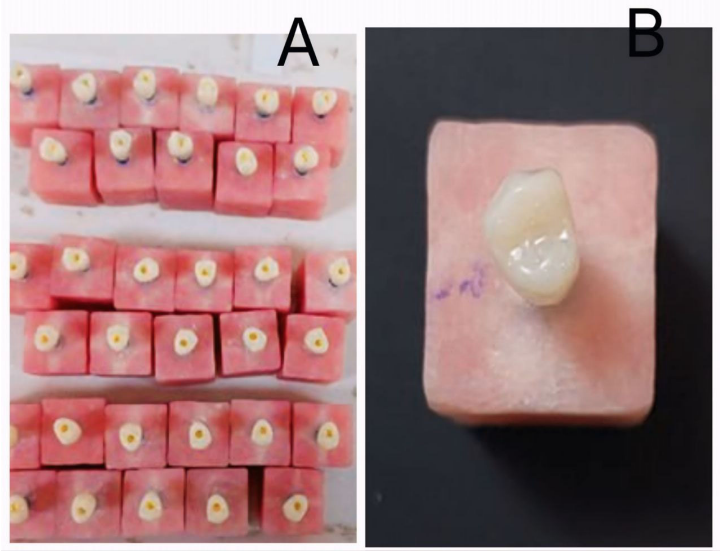


Figure 5. Closing the screw channel: after closing the screw holes with Teflon tape: (**A**), we fill the channel with composite: (**B**).

2.10. Artificial Aging

This process involved both thermal cycling and mechanical fatigue loading.

Thermocycling was performed for 500 cycles between 5 °C and 55 °C, with a 30 s dwell time in each bath, using an automated thermocycling apparatus. The selection of 500 cycles was based on the operational limits of the device and corresponds to a short-term thermal aging condition commonly used in previous investigations of implant-supported restorations [19,30].

Mechanical aging was then performed using 120,000 loading cycles at 50 N and 1.0 Hz. This loading duration has been reported in recent in vitro studies to approximate roughly six months of functional masticatory activity in zirconia implant-supported restorations [31,32]. The cyclic loading was conducted using a chewing simulator (Figure 6), in which the specimens were fully immersed in water, which was replaced every 24 h to maintain consistent hydration conditions. The loading device was paused every 50,000 cycles to inspect the specimens under ×7 magnification for signs of chipping, cracking, or bulk fracture. Water immersion during cyclic loading ensured clinical relevance by simulating oral wet fatigue conditions.

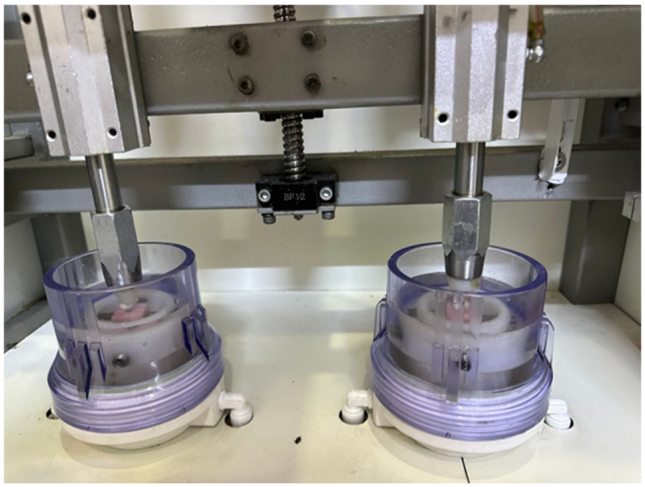


Figure 6. A cyclic loading machine used to simulate six months of oral service by applying 120,000 cycles.

2.11. Measurement of Post-Loading Removal Torque (RVT2)

Following thermocycling, the screw tunnel was accessed, the PTFE barrier was withdrawn, and post-loading screw removal torque values were recorded using the same digital torque gauge (RTV2). The removal torque loss ratio (RTL%) was calculated using the following formula [28]:

$$\text{RTL } \% = (\text{RTV1} - \text{RTV2})/\text{RTV1}$$

2.12. Statistical Analysis

The normality of the data was verified using the Shapiro–Wilk test. Paired *t*-tests compared RTV1 and RTV2, and one-way ANOVA assessed differences in RTL%. Significance was set at $p < 0.05$. Then, post hoc analysis (Tukey's test) was performed and significance was set at $p < 0.05$.

3. Results

3.1. Normality Test

The Shapiro–Wilk test was used to examine the normality of removal torque values in all groups. As shown in Table 2, the data in Groups A, B, and C were normally distributed ($p > 0.05$), indicating that parametric statistical tests were appropriate for further analysis.

Table 2. The Shapiro–Wilk test assessed the normality of removal torque values.

Group	Statistic	df	Sig.
Group A (one-piece hybrid abutment crown)	0.90	12	0.17
Group B (two-piece restoration)	0.94	12	0.62
Group C (stock abutment with zirconia crown)	0.90	12	0.18

3.2. Paired t-Test Comparing Removal Torque Before and After Aging

The paired *t*-test analysis revealed a significant reduction in removal torque values after thermo-mechanical aging in all groups ($p < 0.001$), as shown in Table 3:

In Group A, the mean removal torque decreased from 31.6 Ncm to 27.9 Ncm.
In Group B, torque decreased from 31.1 Ncm to 28.7 Ncm.
In Group C, torque decreased from 31.5 Ncm to 28.9 Ncm.

Table 3. Paired *t*-test between RTV1 and RTV2.

Group	Pairs	Mean Diff (Ncm)	SD	95% CI	*t*	*p*-Value
A	RTV1-RTV2	3.8	0.3	3.99–3.61	40	<0.001
B	RTV1-RTV2	2.3	0.2	2.43–2.17	38	<0.001
C	RTV1-RTV2	2.5	0.1	2.56–2.44	54	<0.001

These results demonstrate that all abutment configurations experienced reduced screw preload following aging.

3.3. Torque Loss Percentage (RTL%)

According to Table 4, the one-way ANOVA revealed a statistically significant difference in torque loss percentages among the three groups ($p < 0.001$):

Table 4. One-way ANOVA comparison of loss percentage among groups.

Group	N	Mean of %	Sd (Stander Deviation)	95% CI	MIN	MAX	*p* Value
A	12	12.04	0.97	12.66–11.42	10.6	14.0	<0.001
B	12	7.6	0.69	8.04–7.16	6.2	8.5	
C	12	7.9	0.39	8.15–7.65	7.4	9.3	

Group A exhibited the highest torque loss (12.04 ± 0.97%, 95% CI: 11.42–12.66), while Group C showed a moderate loss (7.90 ± 0.39%, 95% CI: 7.65–8.15). Group B demonstrated the lowest torque loss (7.60 ± 0.69%, 95% CI: 7.16–8.04). These results indicate that the one-piece hybrid abutment crown (Group A) was more susceptible to preload reduction following aging compared to both the two-piece hybrid zirconia abutment (Group B) and the stock titanium abutment with a zirconia crown (Group C), as show in Figure 7.

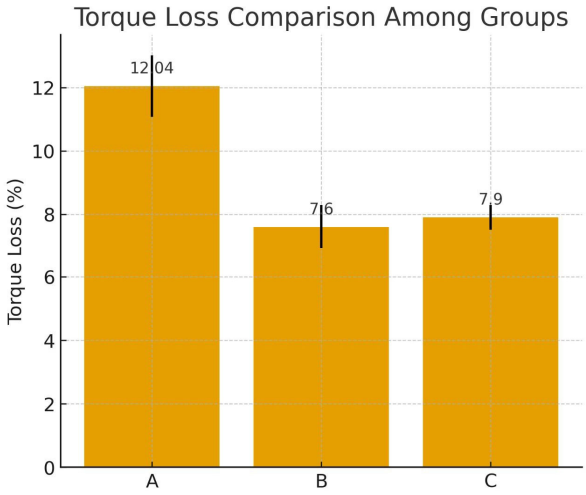


Figure 7. Comparison of torque loss (%) among the three abutment configurations. Group A showed the highest torque loss, while Groups B and C demonstrated comparable stability after aging.

3.4. Post Hoc Analysis

Tukey's post hoc test confirmed statistically significant differences between Group A and both Group B and Group C ($p < 0.001$), while no statistically significant difference was observed between Group B and Group C ($p = 0.53$), as shown in Table 5.

Table 5. Tukey's post hoc comparisons.

Group (I)	Group (J)	Mean Diff	SE	95% CI Lower–Upper	*p*-Value
A	B	4.42	0.30	3.82–5.02	$p < 0.001$
A	C	4.10	0.30	3.50–4.70	$p < 0.001$
B	C	−0.32	0.30	−0.92–0.28	NS ($p = 0.53$)

This indicates that the two-piece hybrid abutment (Group B) and the stock abutment with the zirconia crown (Group C) demonstrated comparable torque stability following aging, whereas the one-piece hybrid abutment crown (Group A) exhibited significantly greater torque loss.

4. Discussion

This study's findings reject the null hypothesis, confirming that abutment design significantly affects screw stability. All tested groups exhibited notably reduced removal torque following thermal and mechanical aging ($p < 0.001$), which is consistent with previous reports indicating that cyclic fatigue and temperature changes compromise screw preload and long-term stability [28,29,33]. The reduction observed here can be attributed to several mechanisms, including resin cement degradation under repeated thermal stresses, suggesting that thermal stresses and mechanical fatigue can erode a screw's capacity to hold torque over time. The integrity of the resin cement may have been impacted by thermal aging, which may have induced hydrolytic degradation and micro-crack formation within the resin cement, reducing its stiffness and altering stress distribution across the crown–abutment assembly. This change likely increased cyclic stresses on the screw joint, leading to gradual preload loss and, consequently, to lower RTV value [34], as well as to wear at the screw–abutment interface that diminishes frictional resistance [33].

Among the three groups, the one-piece hybrid abutment crowns demonstrated the greatest torque loss (12.0%), followed by stock titanium abutments (7.9%), while the two-piece hybrid abutments showed the lowest values (7.6%). Group A (one-piece hybrid abutment crown) exhibited the highest torque loss among the tested configurations. It should be clarified that the screw head in this design was seated on the titanium base rather than directly on the zirconia. Therefore, the increased torque loss can be attributed to micro-settling occurring at the Ti-base–implant interface during thermal and mechanical aging. Since the crown and abutment form a single monolithic assembly, minor interface adaptation under cyclic loading may contribute to preload reduction over time, leading to a greater decrease in removal torque. In this design, the crown and abutment form a single monolithic zirconia structure, eliminating any cement layer between them. This direct and rigid configuration allows occlusal forces to be transmitted more efficiently to the screw joint, with limited damping capacity, which may explain the higher torque loss observed in this group [35].

In contrast, Group B, which utilized a two-piece hybrid configuration, exhibited the lowest torque loss. The presence of a separate crown bonded to a zirconia abutment likely allowed for better stress distribution, reducing the concentrated load at the screw head. This suggests that the restoration–abutment interface may serve as a mechanical buffer to dissipate functional forces.

Group C, consisting of a prefabricated stock abutment with a zirconia crown, demonstrated torque loss values comparable to those of Group B, and no statistically significant difference was found between the two. This similarity may indicate that both configurations provide relatively stable load transfer pathways under functional conditions.

Therefore, the findings of this study suggest that abutment configuration plays a critical role in maintaining screw preload stability during functional loading. These results are consistent with the mechanical concepts described by Siamos et al., who reported that the stability of the screw joint is influenced by the adaptation and behavior of the implant–abutment interface under load [27]. Similarly, Cardoso et al. emphasized that preload preservation is affected by joint configuration and the ability of the interface to resist micro-settlement [36].

In implant-supported restorations, maintaining at least 85–90% of the initial preload after aging is considered indicative of a stable screw joint and a lower risk of mechanical loosening during function. Recent studies on hybrid abutment configurations have reported a similar threshold following thermomechanical loading, supporting this interpretation [18,36]. In the present study, all groups retained removal torque values within this percentage range relative to the initial tightening torque of 35 Ncm, which supports

their classification as clinically acceptable within the controlled laboratory conditions of this in vitro experiment.

This study's observations are partly in line with those of Jongsiri et al. who reported a significant reduction in removal torque across screw-retained, cement-retained, and combined screw- and cement-retained restorations after loading ($p < 0.001$), with no significant variation in RTL% between groups (30.74–35.71%). While their study reported higher RTL% values than those observed here, the difference may be attributed not only to the greater number of cyclic loading cycles employed (500,000 cycles, 20–200 N at 15 Hz) but also to possible methodological variations such as differences in abutment design, torque application protocols, or testing conditions. Nevertheless, both studies consistently indicate that cyclic loading has a strong influence on screw loosening, underscoring the clinical importance of periodic monitoring [29].

Similarly, the findings in [18] found that hybrid abutment crowns experienced greater screw loosening than screw-retained restorations on stock abutments, supporting the finding that the abutment configuration directly influences the mechanical stability of the screw joint. The increased torque loss in one-piece designs noted in both studies may be attributed to the continuous zirconia structure, which transfers functional forces more directly to the screw head with limited capacity for elastic strain dissipation [18].

Other studies have emphasized different contributing factors. For instance, Hendi et al. demonstrated that abutment height can strongly influence screw stability, with taller abutments showing greater torque loss [28]. In this study, however, abutment height was standardized across groups, excluding it as a confounding variable and highlighting restoration design as the key determinant of screw stability.

This study's results contradict those reported by [37,38], who suggested that screw loosening is more likely to occur in crowns fabricated independently of the abutment. This inconsistency may be attributed to methodological differences. Jemt's investigation was performed on titanium blocks with pre-fabricated joint zones, a design feature that may have reduced the likelihood of screw loosening typically observed in one-piece restorations. Similarly, Aalaei et al. employed finite element analysis (FEA), which, while valuable, is limited in clinical applicability since it assumes that materials are homogeneous, isotropic, and linearly elastic [37,38].

Overall, this investigation highlights that while all abutment designs are susceptible to torque loss after functional aging, the magnitude of loosening is significantly affected by the design configuration. One-piece zirconia-based crowns transmit more stress directly to the screw, whereas two-piece hybrid abutments provide a protective buffering effect. Nonetheless, all groups preserved screw stability within acceptable limits, underscoring the clinical relevance of monitoring screw tightening protocols and abutment design selection in long-term implant success.

Beyond abutment design, biological and mechanical factors may contribute to screw loosening during function. Microbial accumulation and the inflammatory response have been associated with micromovement at the implant–abutment interface, which may gradually reduce screw preload. In addition, preload stability depends on frictional behavior, surface contact settling, and the mechanical properties of the screw–abutment assembly. certain adjunctive measures have been explored to improve screw preload stability. Bratu et al. reported that using a screw sealer at the screw–abutment interface may reduce micro-movement and micro-gaps, thereby helping to maintain preload during function. While screw sealers were not applied in this study, their reported benefit suggests that chemical reinforcement strategies may complement abutment design in mitigating screw loosening [39].

Moreover, restorative strategies can influence long-term stability. Mihali et al. [40] demonstrated that sealing the screw demonstrated that sealing the screw access opening with ceramic inlays improved marginal adaptation and reduced occlusal wear and microleakage while maintaining restoration retrievability. These findings indicate that mechanical design features and restorative sealing techniques may act synergistically to support long-term screw joint stability [40].

These findings support the notion that restorative finishing techniques can play a role in controlling micromotion and preserving screw stability in zirconia-based restorations.

From a clinical perspective, the choice of abutment configuration should account for the expected mechanical loading conditions and the need for retrievability. The two-piece hybrid abutment demonstrated the lowest torque loss in this study, suggesting that separating the crown and abutment components may contribute to improved preload maintenance. Meanwhile, the stock abutment with a zirconia crown showed favorable torque stability, making it a predictable and clinically familiar option. However, the one-piece hybrid abutment crown exhibited greater torque loss, indicating that its use may require more frequent follow-up and retightening protocols, especially in patients with higher occlusal load.

5. Limitations

This in vitro study was conducted under controlled laboratory conditions that did not fully replicate the complexity of the oral environment. The thermocycling protocol was limited to 500 cycles due to equipment capacity constraints. While this protocol has been applied in previous in vitro investigations, it may not fully replicate long-term intraoral thermal fluctuations. Future research with extended thermocycling and prolonged fatigue loading is recommended to more accurately represent clinical aging conditions. In addition, factors such as saliva composition, temperature variation, enzymatic activity, and bacterial biofilm were not reproduced by this experimental model. Therefore, although the results provide useful insight into mechanical behavior, clinical studies are needed to confirm their applicability in vivo.

6. Conclusions

Within the limitations of this in vitro study, all abutment configurations demonstrated reduced screw preload following aging. The one-piece hybrid abutment crown presented the highest torque loss, while the two-piece hybrid zirconia abutment and the stock abutment designs maintained comparatively better preload stability under the applied conditions. These findings indicate that the abutment configuration plays a role in screw joint stability; however, the results should be interpreted cautiously, as laboratory conditions do not fully replicate the biological and functional variables of the oral environment. Further long-term clinical investigations are recommended to validate these findings. Future studies may investigate whether optimizing abutment design in combination with screw sealants or restorative sealing techniques provides synergistic improvements in long-term screw joint stability. Clinically, incorporating periodic maintenance and retightening protocols may help minimize long-term screw loosening and improve the stability of implant-supported zirconia restorations.

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Abbreviations

The following abbreviations are used in this manuscript:

°C	Degree Celsius
µm	Micrometer
ANOVA	Analysis of Variance
CAD/CAM	Computer-Aided Design/Computer-Aided Manufacturing
CI	Confidence Interval
Hz	Hertz
IRB	Institutional Review Board
N.cm	Newton Centimeter
PMMA	Polymethyl Methacrylate
PTFE	Polytetrafluoroethylene
RTL%	Removal Torque Loss Percentage
RTV	Removal Torque Value
SD	Standard Deviation
SE	Standard Error
STL	Standard Tessellation Language (file format)
Ti-base	Titanium Base

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