ISSN 0973-2063 (online) 0973-8894 (print)

Bioinformation 22(8): 5002-5007 (2026)

BIOINFORMATION
Discovery at the interface of physical and biological sciences

BIOMEDICAL INFORMATICS

www.bioinformation.net
Volume 22(8)

Research Article

Received August 1, 2026; Revised August 31, 2026; Accepted August 31, 2026, Published August 31, 2026

DOI: 10.6026/973206300225002

SJIF 2026 (Scientific Journal Impact Factor for 2026) = 8.478
2022 Impact Factor (2023 Clarivate Inc. release) is 1.9

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Citation: Agarwal *et al.* Bioinformation 22(8): 5002-5007 (2026)

Comparative evaluation of marginal gap and distortion following repeated healing abutment replacement: A SEM study

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Abstract:
Repeated clinical reuse of healing abutments may compromise the implant–abutment interface, although manufacturer reuse limits remain undefined. Therefore, it is of interest to evaluate the surface changes and marginal gap formation in 360 healing abutments after repeated placement–removal cycles. Mechanical deterioration increased significantly with reuse, with marginal gaps rising from 5.189 ± 0.407 µm to 12.866 ± 0.606 µm ($p < 0.001$). Surface pitting, microcracks, thread deformation and marginal discrepancies became evident after repeated cycling and increased with higher reuse frequencies. Thus, data shows the quantitative reuse thresholds that can guide evidence-based clinical protocols to preserve implant–abutment precision and long-term peri-implant health.

Keywords: Dental implants, healing abutment, marginal gap, screw thread, screw head, wear, distortion, surface roughness and scanning electron microscope (SEM), repeated cycles

Background:
Advances in implant design, materials and implant prostheses have led to the development of a predictable and widely accepted treatment modality for the rehabilitation of missing teeth and the use of dental implants. Although success rates are high, patients have higher expectations for long-term function and esthetics have become the focus of optimising the individual implant components, especially the implant–abutment interface **[1]**. Implant–abutment connection is one of the most important factors in relation to the biological and mechanical stability. This interface may experience microscopic discrepancies and structural distortions with repeated placement and removal of healing abutments **[2]**. While minor, these changes can allow for microbial colonisation, microleakage, loss of the preload and screw loosening or mechanical failure **[3]**. Therefore, maintaining a close and stable fit at the implant-abutment interface is crucial to avoid biological and mechanical complications. The mechanical interaction between the healing abutment and the implant fixture can vary with the implant geometry, the internal connection design, the implant thread configuration and the machining accuracy. These characteristics of the implant and its components can affect the mechanical performance of the healing abutment **[4]**. Despite the frequent clinical reuse of healing abutments, limited evidence exists regarding the biomechanical integrity of the abutment screw and internal hex connection after repeated insertion–removal cycles **[5]**. Repetitive tightening and loosening subject the components to cyclic preload forces, potentially leading to surface wear, hex distortion and thread deformation. Over time, such changes may compromise screw retention, enlarge microgaps and contribute to peri-implant tissue inflammation and crestal bone loss **[6]**. Microcaps at the implant–abutment interface, typically ranging from 20 to 150 µm, are considered clinically unavoidable. However, even then the oral microorganisms permit bacterial penetration and fluid exchange, increasing the risk of peri-implant disease through such discrepancies **[7]**. Inadequate adaptation and progressive wear at the interface may further exacerbate joint instability and microgap enlargement under functional loading. Although various experimental methods have evaluated microbial leakage and torque-related changes at the implant–abutment interface, most investigations have focused on static conditions **[8]**. There remains a paucity of research assessing the microscopic distortion of healing abutment hex threads and marginal adaptation following repeated clinical use. Given the protective and transitional role of healing abutments during implant therapy, their structural precision is essential for long-term success **[9]**. Therefore, it is of interest to report the comparatively evaluate marginal gap formation and surface distortion associated with repeated replacement of healing abutments in implant prostheses using scanning electron microscopy.

Materials and Methods:
Study design:
This laboratory-based experimental study was conducted at the Department of Prosthodontics in collaboration with Uttaranchal University, Dehradun, India. This study used dummy dental implants and healing abutments, bone block, dental implant torque ratchet (UFII®, DIO Implant Co., Pusan, Korea) and SEM (ZEISS EVO 18 Scanning Electron Microscope). The characteristics of the dental implant parts are summarised in (**Table 1)**.

Healing abutment surface roughness:
(Table 2) presents descriptive statistics of surface roughness scores, revealing a statistically significant and progressive increase from HA1 to HA3. Post-hoc analysis confirmed highly significant differences between all group pairs **(Table 3),** indicating that repeated screwing and unscrewing cause cumulative surface abrasion and microstructural alterations that may enhance plaque accumulation and adversely influence peri-implant soft tissue health.

Healing abutment screw thread deformation:
Parallel observations were noted in the evaluation of screw thread deformation, with mean distortion scores increasing significantly with increasing cycle ranges **(Table 4).** Pairwise comparisons (**Table 5)** confirmed highly significant intergroup differences, suggesting that repeated mechanical engagement leads to thread wear and deformation, potentially compromising screw preload, increasing the risk of loosening and reducing the mechanical stability of the implant–abutment interface.

Marginal gap:

Marginal gap analysis confirmed the negative effect of repeated abutment manipulation. **Table 6** shows that marginal gaps increased gradually and significantly from HA1 to HA3, suggesting degradation in fit precision with repeated use. The differences between all groups were highly significant in post0hoc comparisons **(Table 7).** From a clinical perspective, such larger gaps are undesirable as they permit bacterial microleakage at the implant–abutment interface, increasing vulnerability to peri-implant inflammation and peri-implantitis.

Table 1: Characteristics of the dental implant

Parameter	Specification
Diameter	5 mm
Length	11 mm
Implant type	Bone type implant system
Surface treatment	Hybrid Sand-blast & Acid-etched (HSA) method
Titanium grade	Grade IV
Connection type	Internal hex with Morse taper connection

Table 2: Comparative evaluation of surface roughness score between groups

Group	Cycles	Mean	Std. Deviation	95% CI	95% CI	'F' statistic	P value
				Lower Bound	**Upper Bound**		
HA1	3–320	1.289	0.14479	1.1854	1.3926	130.061	.000*
HA2	7–430	1.924	0.27019	1.7307	2.1173		
HA3	12–750	3.041	0.2958	2.8294	3.2526		

**=Significant*

Table 3: Pairwise / Post-hoc comparison within groups for surface roughness

Pairs	Mean Difference	Std. Error
HA1 versus HA2	−0.63500*	0.10999
HA1 versus HA3	−1.75200*	0.10999
HA2 versus HA3	−1.11700*	0.10999

**=Significant. ANOVA revealed significant difference (F = 130.061, p < 0.001). All pairwise comparisons were significant.*

Table 4: Comparative evaluation of screw thread deformation score between groups

Group	Cycles	Mean	Std. Deviation	95% CI	95% CI	'F' statistic	P value
				Lower Bound	**Upper Bound**		
HA1	3–320	0.944	0.14976	0.8369	1.0511	267.613	.000*
HA2	7–430	2.16	0.21082	2.0092	2.3108		
HA3	12–750	3.14	0.2623	2.9524	3.3276		

**=Significant*

Table 5: Pairwise / Post hoc comparison within groups for screw thread score

Pairs	Mean Difference	Std. Error
HA1 versus HA2	−1.21600*	0.0951
HA1 versus HA3	−2.19600*	0.0951
HA2 versus HA3	−0.98000*	0.0951

**=Significant. ANOVA demonstrated high statistical significance (F = 267.613, p < 0.001).*

Table 6: Comparative evaluation of Marginal gap between groups

Group	Cycles	Mean	Std. Deviation	95% CI	95% CI	'F' statistic	P value
				Lower Bound	**Upper Bound**		
HA1	3–320	5.189	0.40665	4.8981	5.4799	546.204	.000*
HA2	7–430	8.691	0.52786	8.3134	9.0686		
HA3	12–750	12.866	0.60608	12.4324	13.2996		

**=Significant*

Table 7: Pairwise / Post-hoc comparison within groups for marginal gap

Pairs	Mean Difference	Std. Error
HA1 versus HA2	−3.50200*	0.23257
HA1 versus HA3	−7.67700*	0.23257
HA2 versus HA3	−4.17500*	0.23257

**=Significant. ANOVA showed highly significant differences (F = 546.204, p < 0.001).*

Table 8: Comparative evaluation of overall class score between groups

Group	Cycles	Mean	Std. Deviation	95% CI	95% CI	'F' statistic	P value
				Lower Bound	**Upper Bound**		
HA1	3–320	0.938	0.22812	0.7748	1.1012	74.619	.000*
HA2	7–430	1.986	0.40814	1.694	2.278		
HA3	12–750	3.055	0.48151	2.7105	3.3995		

**=Significant*

Table 9: Pairwise / Post-hoc comparison within groups for overall class score

Pairs	Mean Difference	Std. Error
HA1 versus HA2	−1.04800*	0.1733
HA1 versus HA3	−2.11700*	0.1733
HA2 versus HA3	−1.06900*	0.1733

**=Significant. All intergroup differences were statistically significant (F = 74.619, p < 0.001).*

Table 10: Overall comparison of parameters

Group	Cycles	Surface Roughness Score	Screw Thread Score	Marginal Gap (µm)	Overall Class Score
		(Mean ± SD)	**(Mean ± SD)**	**(Mean ± SD)**	**(Mean ± SD)**
HA1	3–320	1.289 ± 0.145	0.944 ± 0.150	5.189 ± 0.407	0.938 ± 0.228
HA2	7–430	1.924 ± 0.270	2.160 ± 0.211	8.691 ± 0.528	1.986 ± 0.408
HA3	12–750	3.041 ± 0.296	3.140 ± 0.262	12.866 ± 0.606	3.055 ± 0.482

Sample preparation:

Thirty UFII® implants (5 mm diameter × 11 mm length; DIO Implant Co., Pusan, Korea) were inserted into five synthetic bone blocks (UFII®, DIO Implant Co., Pusan, Korea), with six implants placed per block at 4 mm inter-implant distance following standard surgical protocol. Sample size calculation was performed using G*Power software (version 3.0) based on one-way ANOVA to ensure adequate statistical power.

Placement of healing abutments:

The standard healing abutment (HA) of 4 mm diameter was used. The 360 healing abutments were divided into three groups of 120 healing abutments each. Thirty implants were placed in five synthetic bone blocks, each containing six implants, for a total of 30 implants. The implants were randomly assigned to three experimental groups (HA-1, HA-2 and HA-3), with 10 implants per group. To simulate repeated clinical manipulation, each healing abutment was subjected to multiple cycles of screwing and unscrewing on the respective implant. Twelve cycles of screwing and unscrewing were performed per implant for statistical analysis, with each cycle representing a single observation, yielding 120 observations per group (10 implants × 12 cycles) and 360 total observations across all groups. Baseline imaging was performed before mechanical cycling. In addition, standardised healing abutments were subjected to extended cumulative screwing–unscrewing cycles to simulate long-term clinical manipulation. HA1 was cycled at 3, 9, 24, 60, 240 and 320 times; HA2 at 7, 21, 35, 140, 350 and 430 times; and HA3 at 12, 36, 65, 245, 600 and 750 times. A torque ratchet at a final torque of 30 Ncm was used for all samples. Four-sided orientation grooves were created for SEM alignment. Scanning electron microscope (SEM) evaluation: Imaging evaluations were performed at predetermined cumulative cycle intervals for each group: HA-1 (3, 9, 24, 60, 240 and 320 cycles), HA-2 (7, 21, 35, 140, 350 and 430 cycles) and HA-3 (12, 36, 65, 245, 600 and 750 cycles). The cycle intervals were chosen to reflect mechanical fatigue across three phases: early (initial seating and adaptation), intermediate (progressive wear) and late (cumulative fatigue). After each interval, abutments were removed, ultrasonically cleaned, air-dried and mounted on aluminium SEM pin-type stubs using conductive carbon adhesive tape. All samples were sputter-coated with a thin film of gold to ensure conductivity and prevent charging artefacts. SEM analysis was carried out with standardised operating parameters throughout all specimens. Evaluation covered the hex driver–healing abutment interface, internal and external thread surfaces and the collar area near the implant–abutment interface. Lower magnifications allowed overall morphology assessment and identification of distortion-prone areas, while higher magnifications revealed microstructural changes including surface wear, micro-scratches and abrasion patterns, rounding of hex edges, thread deformation and material loss.

Distortion measurements:

Surface distortion of the healing abutment was examined by SEM using a standardised ordinal grading system (Grade 0–3) adapted to assess progressive surface deformations at the hex driver–abutment interface and screw thread areas:

[1] **Grade 0:** Intact hex surface with no surface irregularity or deformation.

[2] **Grade 1:** Mild surface irregularities consisting of superficial pitting, shallow abrasion lines, or slight micro-cracking without change in overall hex geometry.

[3] **Grade 2:** Moderate surface irregularities with clear deformation of hex edges, significant pitting and some cracking in localised areas, but with some structural integrity retained.

[4] **Grade 3:** Severe surface irregularity with significantly advanced hex distortion, rounding of line angles, significant material loss and clearly compromised structural morphology.

[5] Each specimen was independently graded at each insertion-removal point on this ordinal scale to allow qualitative comparisons across mechanical testing cycles.

Statistical analysis:

Data were analysed using SPSS 24.0 (SPSS Inc., Chicago, IL, USA). Descriptive statistics were computed and tabulated for surface distortion across different screwing–unscrewing intervals. Differences in distortion grades between insertion/removal cycles were assessed using one-way ANOVA and Tukey's post-hoc test to determine statistically significant differences in surface integrity following progressive mechanical manipulation. A p-value of 0.05 was set as the threshold for statistical significance. To eliminate inter-operator variability, all experimental procedures, mechanical cycling, SEM imaging and distortion grading were conducted by a single calibrated investigator.

Results:

There was no surface distortion of the healing abutment screw threads up to 16 cycles. Repeated mechanical cycling caused clear and progressive degradation of the healing abutments, with changes beginning at approximately 24 cycles. After 24, 32, and 40 repeated cycles, mild surface irregularities were observed, characterized by pitting and thread surface distortion **(Figures 2–4)**. The grading criteria used to assess surface distortion from Grade 0 to Grade 3 are presented in **Figure 1**. The overall class score represented the cumulative effects of surface roughness, screw-thread deformation, and marginal changes. Group HA3 showed the highest overall class scores, whereas HA1 demonstrated minimal structural compromise **(Table 8)**. Statistically significant differences were observed among all groups, as confirmed by post-hoc analysis **(Table 9)**. These findings demonstrate the additive effects of mechanical degradation with increasing fatigue cycles. **Table 10** provides a comprehensive comparison across all evaluated parameters, demonstrating parallel and progressive deterioration following repeated mechanical manipulation. The SEM findings further demonstrate increasing thread wear and deformation across the HA1, HA2, and HA3 groups **(Figures 2–4)**. Overall, repeated screwing and unscrewing of healing abutments significantly affected surface characteristics, screw-thread integrity, marginal fit, and mechanical performance. Repeated handling may induce structural changes that compromise implant–abutment fit, potentially contributing to microleakage and an increased risk of peri-implant tissue inflammation. These findings underscore the importance of avoiding unnecessary removal of healing abutments and implementing controlled reuse protocols to maintain long-term peri-implant health.

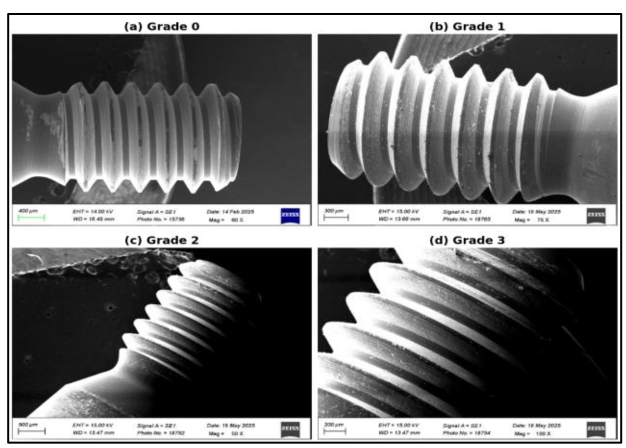

Figure 1: (a-d): Grading criteria for surface distortion (Grade 0–3)

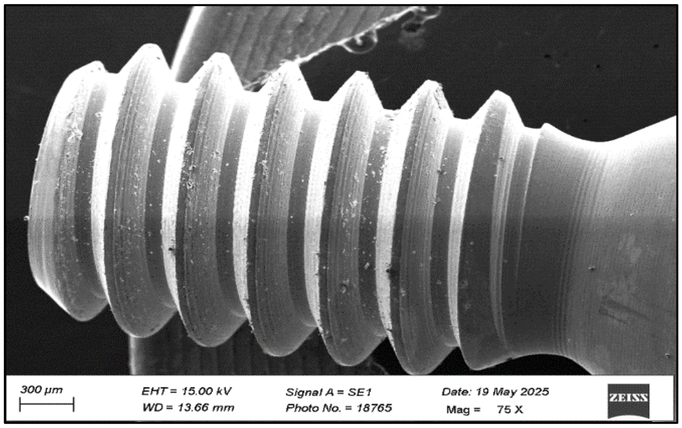

Figure 2: SEM image of screw thread interface after low cycle exposure (HA1 group)

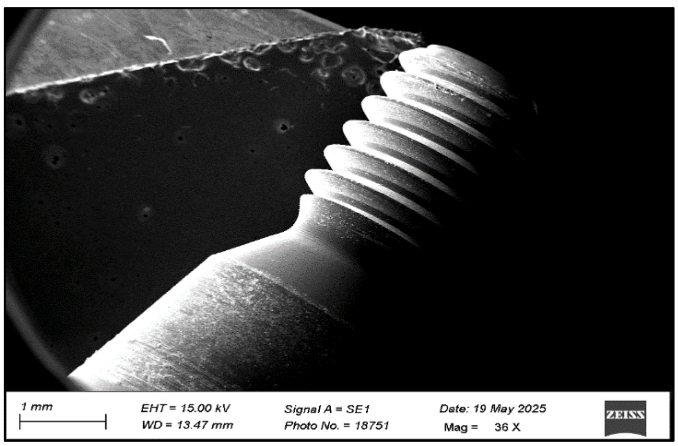

Figure 3: SEM image showing moderate thread wear in HA2 group

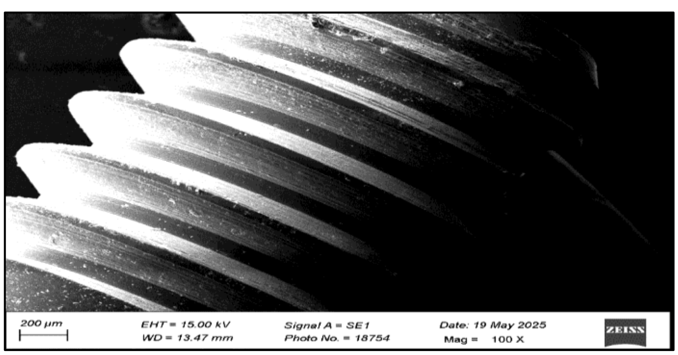

Figure 4: SEM image depicting severe thread deformation and surface irregularities in HA3 group

Discussion:

The present *in vitro* SEM study revealed a clear and progressive relationship between the number of placement–removal cycles and structural deterioration of healing abutments. Increasing cycles caused a progressive rise in mean distortion scores across all evaluated parameters, with the highest-cycle group showing the greatest deterioration. Statistical analysis verified that repeated mechanical manipulation has a significant negative effect on the structural integrity of healing abutments. Distortion was negligible during early cycles but became statistically significant beyond approximately 24 placement/removal events, with wear patterns steadily increasing thereafter, indicating that mechanical fatigue accumulates over time. Surface roughness increased significantly with progressive cycling, indicating cumulative abrasion and microstructural disruption, with clinical significance for plaque retention and peri-implant soft tissue response. Similar trends were observed for screw thread deformation, where statistically significant deformation at higher cycle counts may lead to loss of preload, mechanical instability and increased risk of screw loosening **[10].** Marginal gap analysis showed statistically significant increases in marginal discrepancy with repeated reuse, with fit precision clearly lost after only a few additional placement–removal cycles—a biologically undesirable outcome given the risk of bacterial microleakage and peri-implant inflammation. The overall class scores indicated additive mechanical degradation rather than isolated defects, with cumulative deterioration observed across surface morphology, thread integrity and marginal adaptation **[11]**. Tallarico *et al.* (2018) **[12]** studied the long-term mechanical performance of abutments with internal connections through multiple tightening cycles. After 20 cycles, surface wear was observed by SEM and reverse-torque values decreased, affecting mechanical retention and sealing precision. The use of SEM in the present study allowed subtle surface changes to be visualised at high magnification that could not be achieved by other techniques such as 3D profilometry or digital superimposition. SEM images showed pitting, microcracks and localised deformation patterns consistent with cyclic fatigue damage. Siadat *et al.* (2018) **[13]** performed a literature review comparing microleakage and screw loosening in two implant–abutment connection designs, finding that cyclic loading led to increased microleakage and mechanical instability after approximately 24 to 32 cycles. Notable structural changes in the present study align with findings previously reported by D'Ercole *et al.* (2014) **[14]**. Foong *et al.* (2020) **[15]** compared mechanical wear and microgap formation at implant–abutment junctions under cyclic stress, showing that repeated loading and screw retightening lead to plastic deformation, surface wear and time-dependent deterioration in fit quality and increased bacterial penetration. The present findings corroborate these trends. There are serious clinical implications from this study. Rougher surfaces facilitate bacterial penetration at the implant–abutment junction, increasing the risk of peri-implant infection. Compromised thread integrity can lead to screw loosening and loss of mechanical stability. The observed threshold suggests that reuse beyond 24–36 cycles is unfavourable and the introduction of tracking protocols to monitor placement–removal cycles per healing abutment may improve clinical safety and implant system reliability. The study has limitations inherent to its *in vitro* design. Oral parameters such as saliva, temperature changes, functional loading and sterilisation cycles were absent, which could influence wear behaviour. Only one implant–abutment system was tested, limiting generalisability to other systems (internal hex, external hex, or Morse taper). There was no direct measurement of bacterial microleakage or evaluation of biological response to surface irregularities. Further studies should incorporate environmental simulation, sterilisation procedures and dynamic loading. Comparison of different implant–abutment geometries, materials and novel wear-resistant surface treatments and coatings would also be valuable. Finite element analysis may provide additional understanding of stress distributions and fatigue behaviour under cyclic loading.

Conclusion:

Repeated reuse significantly increased marginal gap, surface roughness, thread deformation and structural distortion of healing abutments. Mechanical deterioration became evident beyond approximately 24 reuse cycles, indicating compromised implant–abutment fit. These findings support evidence-based reuse limits to preserve mechanical stability and long-term peri-implant health.

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