OPEN ACCESS

Saudi Journal of Oral and Dental Research
Abbreviated Key Title: Saudi J Oral Dent Res
ISSN 2518-1300 (Print) | ISSN 2518-1297 (Online)
Scholars Middle East Publishers, Dubai, United Arab Emirates
Journal homepage: https://saudijournals.com

Original Research Article **Oral and Maxillofacial Surgery**

The Influence of Dental Implant Thread Geometry on Failure Modes and Fracture Behavior

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DOI: https://doi.org/10.36348/sjodr.2026.v11i02.004 | **Received:** 06.12.2025 | **Accepted:** 04.02.2026 | **Published:** 09.02.2026

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Abstract

The objective of this study was to evaluate the influence of variable dental implant thread shapes upon the failure mode and fracture behavior. Sixty custom made grade 4 titanium dental implants screws were manufactured according to the type of thread form and classified into; V-Form (Group 1), Square Form (Group 2), Buttress Form (Group 3) and Reverse But-tress Shape (Group 4); with Standard lab analysis set up following ISO14801 Protocol. The implants were mounted in an acrylic block and subjected to a 30° off-axis compression loading using Universal Testing Machine (UTM). The mode of failure was analyzed using a Stereomicroscope. The fractured surfaces of failed specimens were examined using Scanning Electron Microscope (SEM). The results showed that there was no statistically significant difference between the groups in terms of the failure mode distribution ($p>0.05$). Four different failure types were observed: Breaking the fixture and screw, breaking the abutment and screw, breakage of the screw or deformation of the hole implant system part. SEM fractography examination indicated a ductile fracture mechanism through plastic deformation of the implants fixture and abutment screws. Additionally, four distinct failure modes were identified: fixture and screw fracture, abutment and screw fracture, screw fracture, and hole implant component deformations. SEM fractography analysis showed a ductile fracture mode with plastic deformation of the implants fixture and abutment screws. The results of this study suggest that different thread forms failure mode was almost identical in all thread design.

Keywords: Dental Implants; Thread Shapes; Failure Mode; SEM.

INTRODUCTION

Osseointegration of an implant depends on mechanical stability and biological stability attained during the healing period of bone. Factors that affect the stability of the implant include osseous quality, the configuration of the implant, and method of insertion; however, bone quality is a key to the long-term success or failure. The poorly trabeculated bone, especially in the posterior maxilla with predominant cancellous bone results in difficult attainment of primary stability and a high risk of early implant failure. Thus, the implant geometry and thread design need to be carefully chosen, even for poor bone quality or immediate implant installment. Within the most frequently used designs, tapered implants have been shown to achieve greater primary stability than parallel implants in both clinical and in vitro studies [1, 2].

Many kinds of thread have been designed and tested for efficient force insertion and transmission. Thread form is determined by thread pitch and face angle. V-shape, Square, Buttress or Reverse Buttress. Self-taping of the V shape threads are generally assumed, with a theoretical argument for a square or buttress form as well to transmit more of the occlusal force into favorable compressive rather than shear [3].

Dental implants have been an excellent treatment alternative for completely or partially edentulous patients. A serious condition resulting from the fracture of an osseointegrated implant is one that may lead to the loss of supporting tissue. Despite its more than 90% rate of success, it has occasionally been reportedly linked to rare fractures [4]. According to Goodacre *et al.*, the probability of implant body fractures during the early to middle period is 0% for implants with a diameter of 3.75 mm, 2% for fractures of abutment screws, and 2% for screws used in prostheses [5].

Among all mechanical problems, implant fractures are regarded the most aggravating since they may develop after a period of function. The literature indicates a wide range (0.0% to 3.45%) in the incidence of implant fractures [6]. Fracture strength is a kind of stress that is related to fracture stress. It is critical to know a material fracture stress since its lifespan is dependent on its fracture resistance when it develops a crack [7]. Previous in-vitro research has examined the impact of different factors on implant static fracture strength, but no literature data on the influence of implant thread shapes on fracture strength are known. The present research used various dental implant thread forms to evaluate the impact of these design shapes on dental implant fracture strength and to investigate the fracture mechanism.

Currently there is a little information available on the effect of implant thread design on overall implant strength, and no direct comparisons of available thread designs have been reported. Therefore, this study aimed to evaluate the influence of variable dental implant thread shapes (V-shape, square-shape, buttress-shape and reverse buttress-form) upon the failure mode and fracture behavior of dental implants. The null hypothesis, there is no difference in the failure mode and fracture behavior among dental implants groups with V-shape, square-shape, buttress-shape and reverse buttress-form thread design.

MATERIALS AND METHODS

A total of 60 custom made bone level dental implants Ti-GR4 was utilized int the study. The implants were similar in size, surface topography, body design and material but have a different thread type which are (V, square, buttress and reverse buttress). The materials used in this study and their description as well as the manufacturer's recommendations are summarized in Table 1.

Table 1: Specifications of the used dental implants.

Specification of the implants				
Implant thread shape	**V-shape**	**Square shape**	**Buttress shape**	**Reverse buttress shape**
Diameter	4.1 mm	4.1 mm	4.1 mm	4.1 mm
Length	10 mm	10 mm	10 mm	10 mm
Implant Type	Bone Level	Bone Level	Bone Level	Bone Level
material	Ti-GR4(ASTM F67)	Ti-GR4(ASTM F67)	Ti-GR4(ASTM F67)	Ti-GR4(ASTM F67
Fixture design	Self-taping	Self-taping	Self-taping	Self-taping
Surface treatment	SLA	SLA	SLA	SLA
Surface roughness	1.8µm	1.8µm	1.8µm	1.8µm
Thread depth	0.44 mm	0.44 mm	0.44 mm	0.44 mm
Connection type	Conical	Conical	Conical	Conical
Abutment Specifications				
Material	Ti-GR5 (Ti–6Al–4V alloy)			
Gingival hight	4 mm			
Diameter	5 mm			
Torque	30 Ncm			
Lot no	PAD50GH4M18191004			

The specimens prepared by mounting each implant in an acrylic block (Orthodontic Base Polymer Self-Cure Acrylic Resin). The specimens were classified into four groups (n= 15 per group) according to threads type, namely V-Shape (Group 1), Square Shape (Group 2), Buttress Shape (Group 3), and Reverse Buttress Shape (Group 4). The specimens were positioned at a 30 ± 2° to the loading axis (To simulate a strong single tooth bending force or cantilever load) and attached to a fixation device. Compressive load was applied utilizing Universal Testing Machine (UTM). The test fixture together with specimens was mounted 30° angle with the respect to the applied load according to ISO 14801 standardizations [8]. The mode of failure was analyzed using a Stereomicroscope. The fractured surfaces of failed specimens were examined using Scanning Electron Microscope (SEM).

Each sectioned surface was first examined by using a Stereomicroscope (Discovery Series V20 Stereomicroscope, Carl Zeiss, USA/Canada, Seri No: 1364-171) interfaced to a monitor and PC and linked to a high-resolution video camera (PHILIPS) to determine the fracture site and the relative position from the simulated bone. Images were subsequently processed and analyzed using ZEN 2 (BLUE EDITION) Software.

The sectioned specimens were cleaned with liquid soap and washed for 5 min in diluted acetone solution (1:3 in distilled water) using ultrasonic cleaner (General Home Ultrasonic Cleaner, model no: AS-8772, Freq., 50Hz, China). it needs to take care not to touch the fractured samples to avoid surface contamination. Fractured surfaces of failed specimens were examined using SEM (Carl Zeiss AG - EVO 40 Series, USA)

Statistical analysis

The data of the research was analyzed by IBM SPSS 22.0 statistical package program and number, percentage, mean ± standard deviation, median, minimum- maximum values were given. Normal distribution for quantitative data was examined by the Shapiro-Wilk's test. On the intergroup comparisons of parameters with normal distribution One-way ANOVA test was employed and since homogeneous data Tukey HDS test was used to define which group causes the difference on the Tukey analyses. A p-value <0.05 was considered statistically significant.

RESULTS

The results of the mechanical tests were analyzed using macrofracture mode analysis to determine the various fracture modes present in each specimen. In the majority of cases, the failure mechanism was almost similar, including persistent deformations of the framework in the implant neck region. The main modes of failure were fracture and deformation. (Figure 1-7)

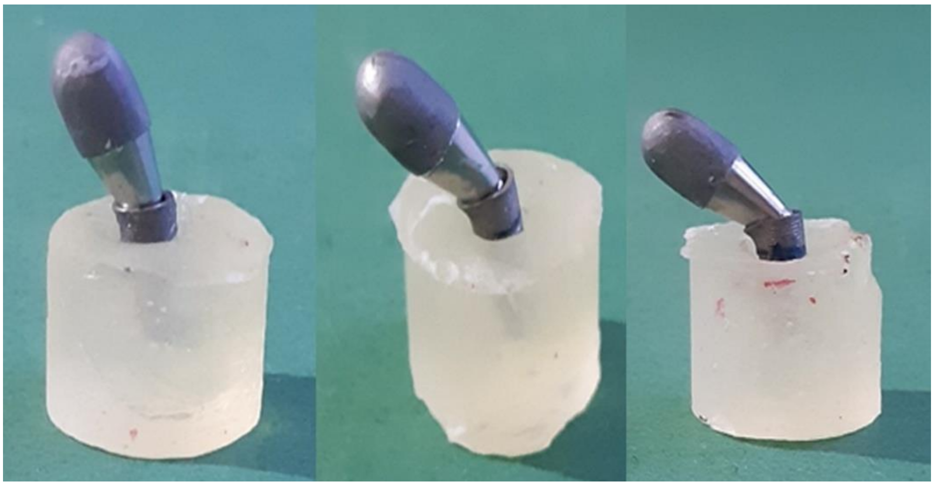

Figure 1: Deformation of dental implant specimens.

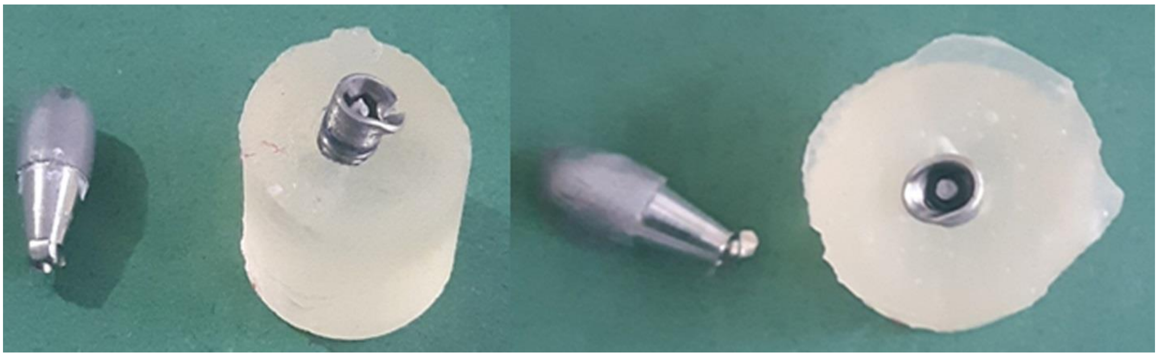

Figure 2: Fracture of Dental implant specimens.

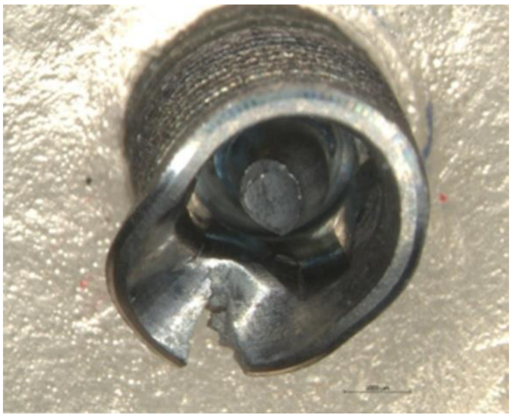

Figure 3: Fixture and screw fracture failure mode revealed by Stereomicroscope (magnification 1000 µm), (top view).

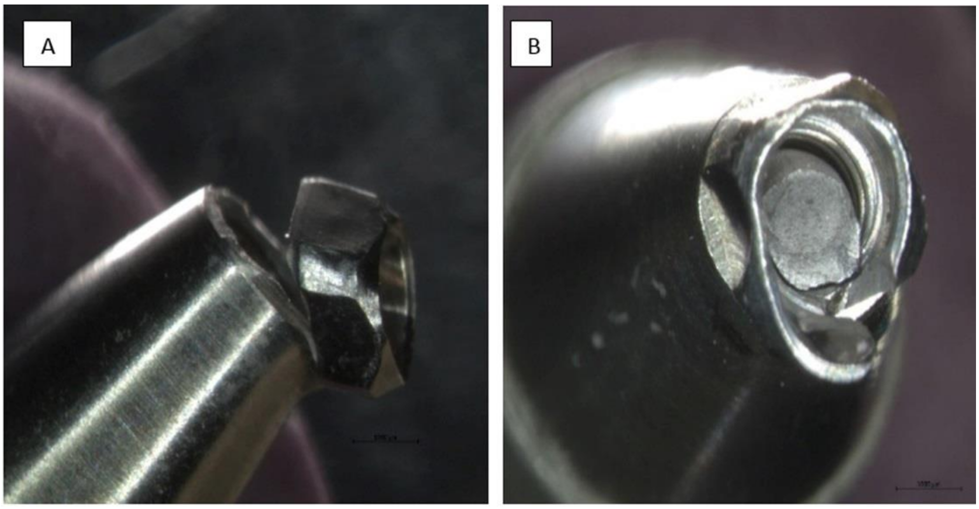

Figure 4: Different forms of abutment and screw fracture failure mode revealed by Stereomicroscope (magnification 1000 µm). A) Horizontal fracture (side view), B) Vertical fracture (top view).

Figure 5: Screw fracture failure mode with fixture neck deformation revealed by Stereomicroscope (magnification 1000 µm), (top view).

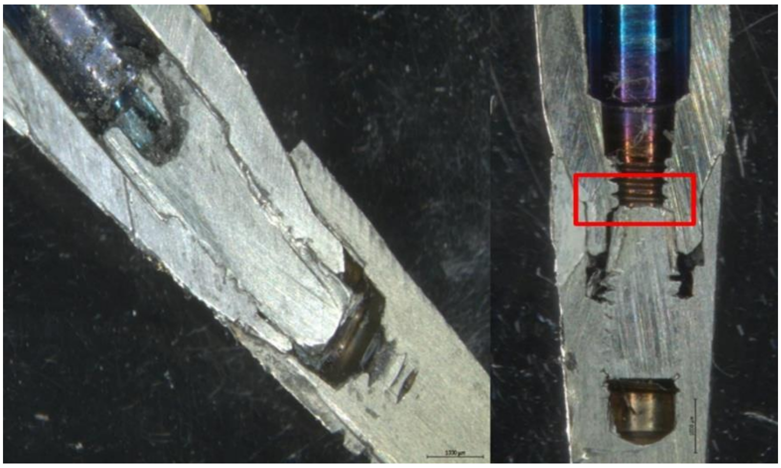

Figure 6: Longitudinal section of implant/abutment sets of the failed system taken by stereomicroscope (magnification 1000 µm) showing internal screw fracture.
(A) lower part screw fracture, (B) Upper part screw fracture.

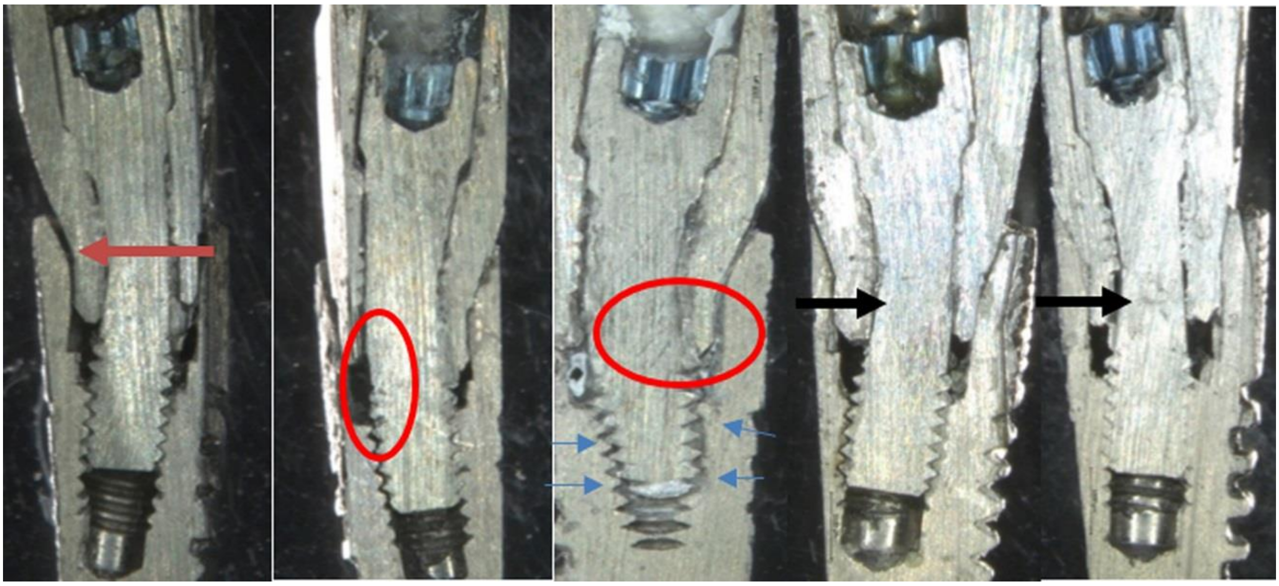

Figure 7: Longitudinal section of implant/abutment sets of the failed system taken by stereomicroscope (magnification 1000 µm) showing, fixture-abutment-screw deformation and bending failure mode. gap formation between implant fixture and abutment (black arrow), misfit between the coils of the screw and the internal coils of the implant (blue arrows) It could be hypothesized that the misfit was due to widening of the fixture diameter in the direction of the applied load. A particular of the bent screw and fixture (black arrow).

According to Fisher's Exact Chi-Square test were used for comparison of qualitative data. There was no statistically significant difference between the groups in terms of the failure mode distribution (p:0.900; p>0.05). Hole implant system deformation was observed in 46.7% of Group 1, 33.3% of Group 2, 40% of Group 3 and 46.7% of Group 4, as seen in Table 2 and Figure 8.

Table 2: Evaluation of The Groups in Terms of Failure Mode Types.

	Group 1	**Grpup 2**	**Group 3**	**Group 4**	***Total***	
Failure Mode Type	**n (%)**	**n (%)**	**n (%)**	**n (%)**	***n (%)***	**p**
Fixture and Screw Fracture with Abutment Distortion	2 (%13,3)	5 (%33,3)	4 (%26,7)	3 (%20)	*14 (%23,3)*	0,900
Abutment and Screw fracture with Fixture Distortion	2 (%13,3)	3 (%20)	1 (%6,7)	3 (%20)	*9 (%15)*	
Fracture Screw only	4 (%26,7)	2 (%13,3)	4 (%26,7)	2 (%13,3)	*12 (%20)*	
Hole Implant System Deformation	7 (%46,7)	5 (%33,3)	6 (%40)	7 (%46,7)	*25 (%41,7)*	

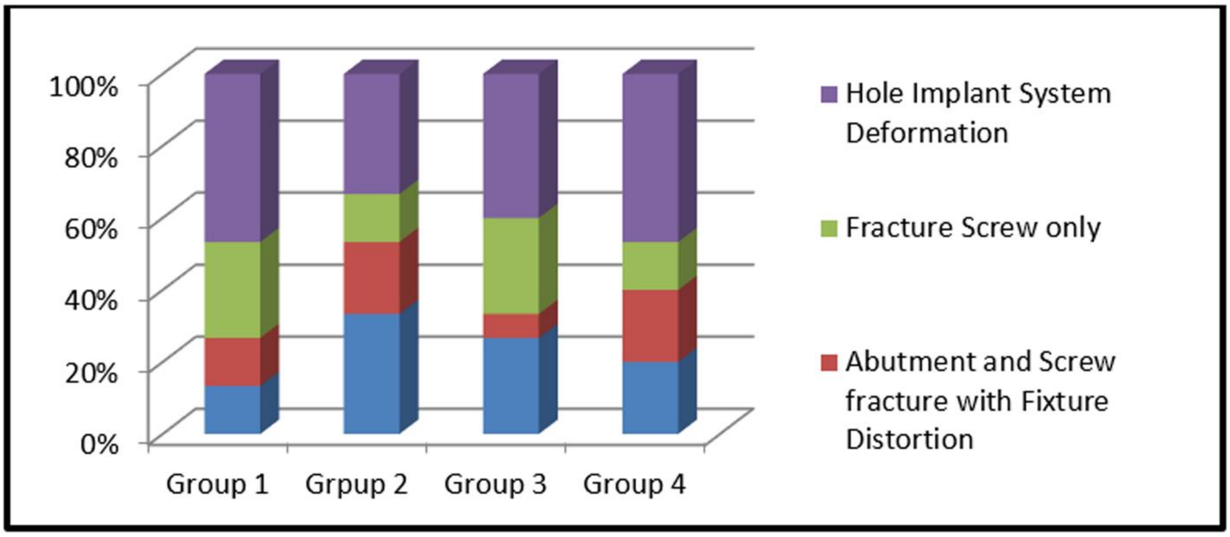

Figure 8: Bar chart illustrates failure mode distribution. Further evaluation of fractographic analyses was conducted using SEM micrographs (figures 9-16).

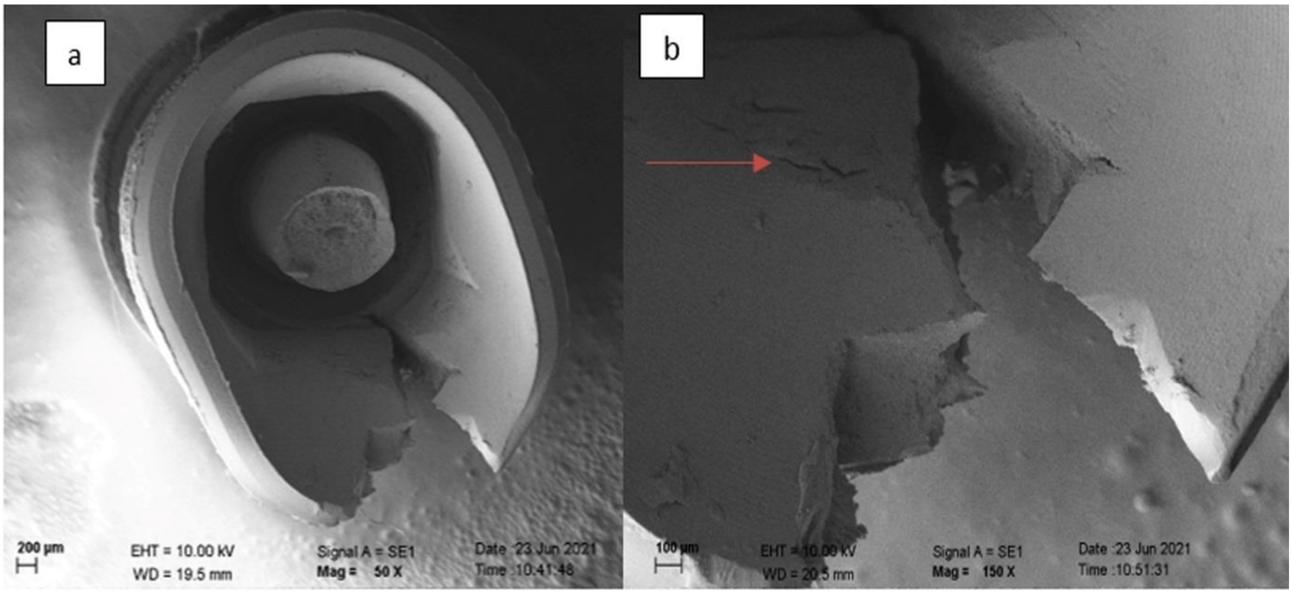

Figure 9: SEM Fractography of failed specimen: (a) SEM micrograph of fixture neck and screw fracture (top view) (magnification= 50X) showing fracture line extending along with implant fixture, (b) SEM micrograph in 150X magnification showing horizontal crack fractures; the red arrow marks the place of crack.

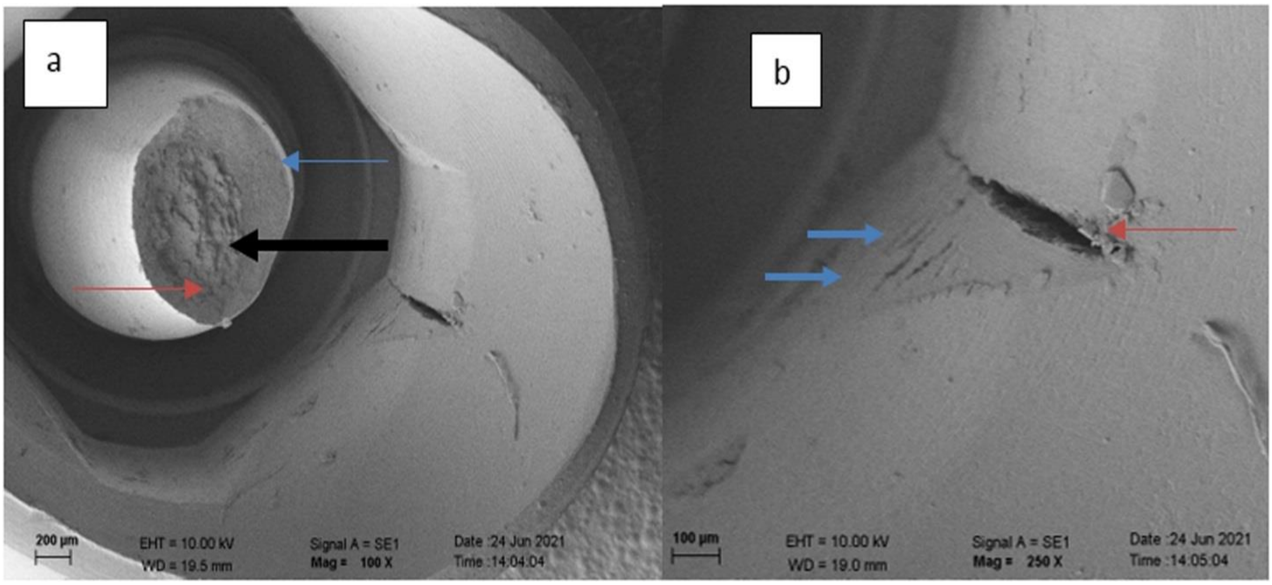

Figure 10: a) Typical SEM Micrographs of the fracture surface of a failed abutment screw. Showing Dimples (black arrow) which are characteristic of ductile failure, the boundary can be seen between smooth (upper right blue arrow) and rough surfaces (lower left red arrow), (magnification 100X). b) SEM images in 250X magnification show the plastic deformation and fracture failure of fixture extending from the platform along the body of implant accompanied by multiple horizontal mini fracture cracks originated along with the main crack (blue arrows) that indicate stress concentrations at the neck of the fixture.

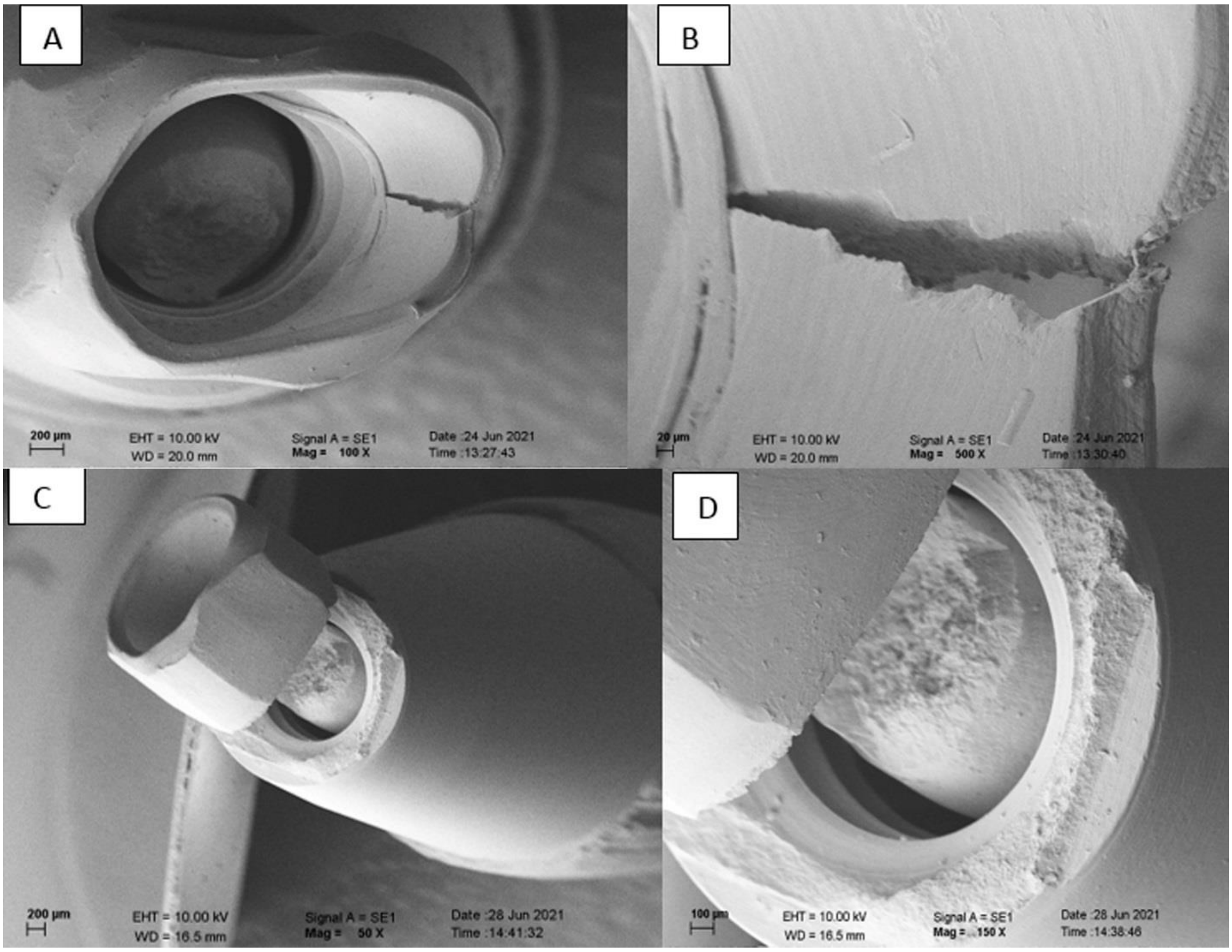

Figure 11: SEM fractography showing an overall view of different types of Abutment fracture; a) vertical abutment neck fracture with screw fracture, b) 500X magnification showing the course of the fracture line, c) horizontal abutment neck fracture, d)150X magnification the fracture surface showing a compression curl, the existence of a compression curl is an important sign that the specimen either was loaded primarily in bending or had strong bending component.

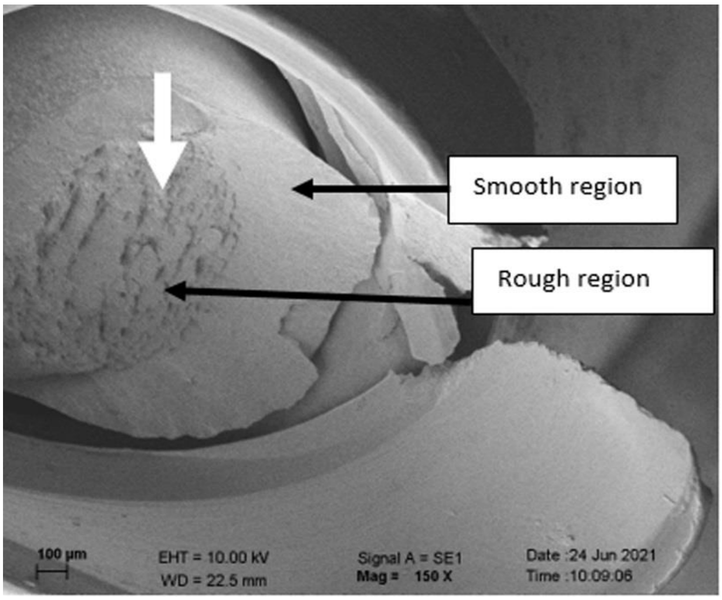

Figure 12: Typical SEM fractography of fractured surfaces is composed of two distinct regions: a smooth region closes to the failure origin and a rough region close to the compression curl. These regions demonstrate a slow mode of ductile fracture, consisting of dimples and micro voids (white arrow), mixed with end-stage of rapid fracture, as indicated by a mirror image of the shiny surface.

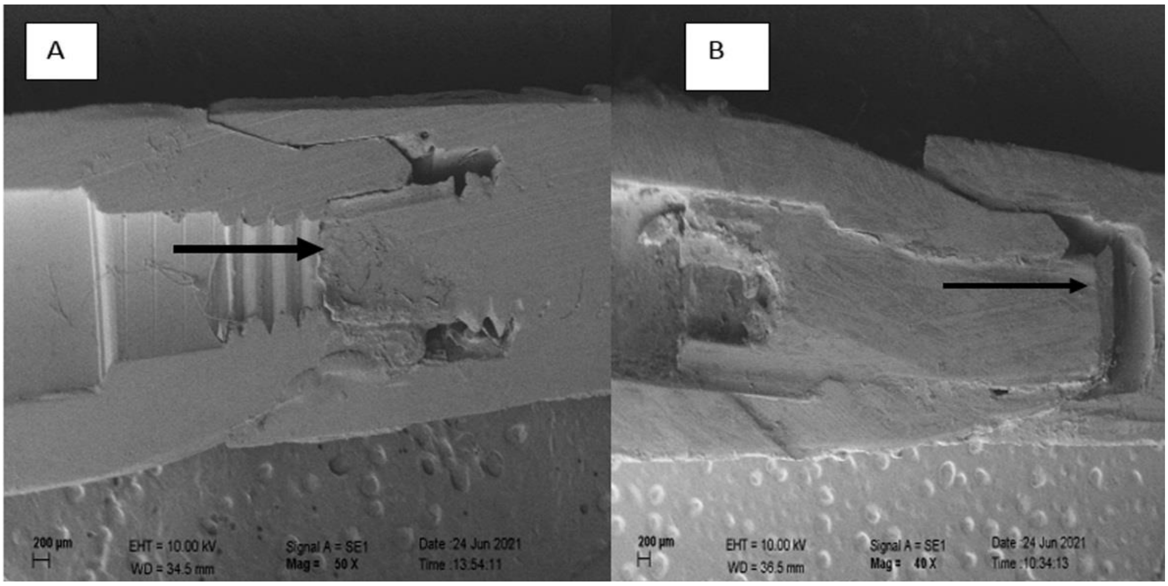

Figure 13: SEM fractography of longitudinal section of hole implant specimen: a) upper part screw fracture, b) lower part screw fracture (magnification 50X).

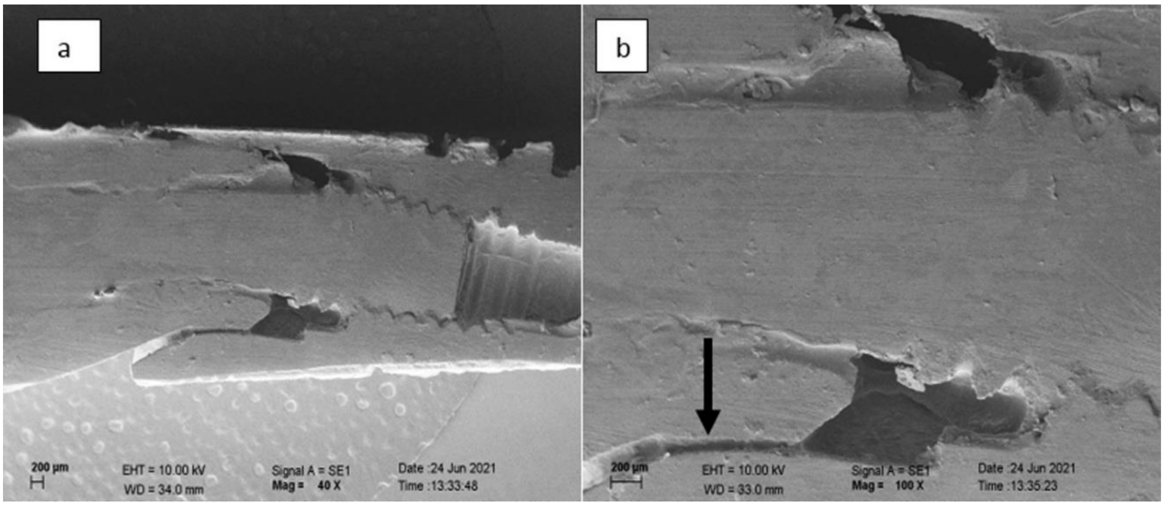

Figure 14: SEM fractography showing; a) plastic deformation of the implant-abutment complex specimen, b) SEM images in 100X magnification showing gap formation between implant fixture and abutment (black arrow).

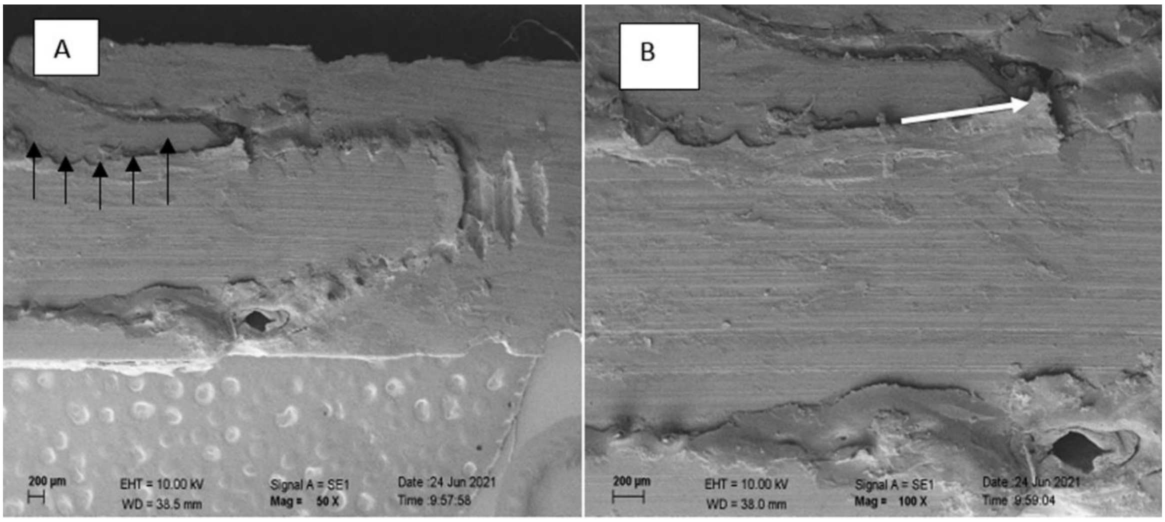

Figure 15: SEM micrography a) lateral view of the implant in the neck region, show bending of the screw in the loading direction (black arrows), b) A particular of the bent screw where crack nucleation is initiated (white arrow).

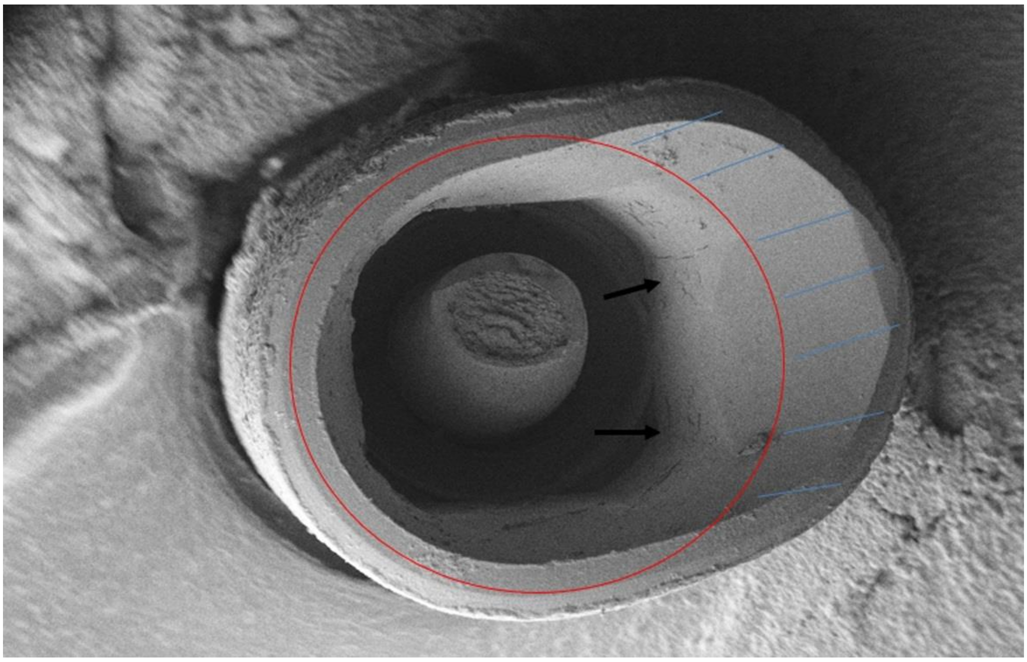

Figure 16: Typical SEM fractography 50X magnification, showing widening of the fixture diameter (plastic deformation) at the neck area with an ovoid shape toward the lingual side (direction of the applied load) (blue arrows) with numerous cracks fractures (black arrows).

DISCUSSION

Dental implants have provided a real improvement in treatment of partial and full edentulous patients, with results significantly preferable to those obtained with conventional fixed or removable partial dentures. Implants offer superior esthetics, function and speech compared with removable prostheses and preservation of both oral hard and soft tissue that make them the first option in terms of replacing teeth [9]. The long-term outcome of dental implants primarily relies on good transmission of occlusal force to the surrounding bone and stability without any resorption [10]. Several factors including, implant geometry, thread formation surface properties, loading conditions and bone quality can have an impact on this biomechanical interaction [11]. Implant thread design, of those variables, is also the most significant in respect to stress distribution at the implant-bone interface that finally influences the primary stability and osseointegration response directly [12]

Thread shape (V-shaped, square, buttress and reverse buttress) of the implants have a significant influence on mechanical and biological stability of dental implants. Mechanical stability, supported by implant threads in contact with bone, is necessary for initial stability; biological fixation by means of osseointegration is essential for long-term survival. The design of the threads affects the area of contact between the implant and bone, which is an important factor regarding osseointegration strength [13].

The current study was conducted in-vitro, which is adequate cost and time effective compared to in-vivo studies. This in vitro testing method is a valid and efficient way to establish the mechanical strength of implants for clinical experimentation. It is standardized and allows to compare the mechanical behavior of different implant types under comparable load and boundary conditions. Previous in-vitro studies have investigated several factors affecting implant static failure load, such as the dimensions (implant or abutment), shape, test design variables, composition of the materials and implant-abutment connections. Similar implant system was used in most of the cases, when the influence of size, material and test procedure were compared [14].

Four screw-retained implant threads were applied in the present study: V thread, square thread, buttress type; and reverse buttress type (categorized based on thread thickness and face angle) [15]. The null hypothesis was accepted, as the results showed no difference in the failure mode and fracture behavior among dental implants groups with V-shape, square-shape, buttress-shape and reverse buttress-form thread design.

The reason for having the maximal fracture strength in samples of reverse buttress thread and V shape thread might be due to the fact that the degree of face angle transfers a greater amount of shear to implant-bone interface, whereas sharp edges could lead to stress concentration on institute interface; hence most distracting forces were consumed by implant bone interface. As long as the face angle of the square threads is not significant, The implanted body might be subjected to compressive occlusal load in axial sides when it has design of square or plateau (buttress) but it will be converted into higher shearing force at bone contact surface if the implant body is designed with V-shaped thread [16].

In terms of failure modes, macro fracture mode analysis was done to identify different fracture modes for all the specimens. Under the stereomicroscope, most of the specimens show permanent deformations of the fixture. The failure mode was almost identical in most of the specimens, including permanent deformations of the framework at the implants neck area, with mainly two patterns of the failure mode phases: fracture or deformation [17].

The current result shows four different failure modes: fracture of fixture and screw with abutment deformations, abutment and screw fracture with fixture deformations, screw fracture only, and deformation (distortion) of hole component. This result came with agreement with Song et. al [18], which conclude that the two-piece SuperLine and NRLine exhibited four distinct modes. Four failure types were observed in the SuperLine group: fixture and screw fracture, screw and abutment fracture, abutment fracture, and minor component deformations. In the NRLine group, failure mechanisms included fixture and screw fracture, fixture, screw, and abutment fracture, and minor component deformation.

In contrast, Shemtov *et al.,* [19], stated that the 2-piece dental implant with three different diameters (3.3), (3.75), and (5 mm) displayed four distinct fracture modes: abutment neck and screw, implant body-neck, implant body-thread, and implant body-thread. However, because of the various experimental factors used in this research, it is difficult to compare failure features described in the literature to those discovered in this study.

Regarding our result, the percentage of fixture and screw fracture was 33.3%, in group 2, and 26%, in group 3, which were relatively higher than group 1 and group 4, with percentage of 13.3% and 20% respectively, but there was no statistically significant difference. Concerning the failure mode, hole implant system deformation was observed in 46.7% of Group 1, 33.3% of Group 2, 40% of Group 3 and 46.7% of Group 4.

The fixture (body) failure mode occurred in the neck region of the present research and was confirmed as the first turning moment at the top of the force-displacement curve, referred to as the failure forces. As a result, the fracture resistance of the whole sample was calculated using the strength around the implant neck at the current loading conditions. More precisely, implant fracture strength was shown to be significantly linked with implant neck wall thickness. According to Misch interpretation of the engineering standard on cylinder fracture strength, increasing the wall thickness of two-piece implants significantly increases the implant fracture resistance [20].

A 30° off-axis load on the implant was incorporated in all Finite Element Analysis (FEA) models, resulting in a force moment that bent the implant to its lingual sides. As a consequence, tension was focused between the first and second threads in the neck, with the lingual side suffering greater stress than the buccal side. These findings are in agreement with those from Sannino *et al.,* [21], FEA study and verified by the current static test in which implant fracture occurred at their neck area. On the other hand, Shemtov-Yona, Keren, *et al.,* [19], reported that, for the 3.75-mm implant, 55.5% were fractured at the implant second thread, which is the dominant fracture mode, and 44.4% of the fractured implants were fractured at the neck of the implant.

All implant systems utilized in this research were grade 4 from the same manufacturer, Except for the abutments, which were made up of titanium alloy (Ti6Al-4V) (Grade 5) which has greater strength than pure titanium. This clearly explains the low percentage of fractures among the abutments. The site of the broken abutment was at the level of the base-implant junction where the stress was concentrated. The abutment screws were had a relatively tiny diameter of 2.0mm and broke under much lower stresses than an abutment or implant wall [22].

Recent study by Camps-Font *et al.,* [23], tested 24 tapered titanium grade 5 dental implants with similar macroscopic and microscopic designs with V-shaped threads (Biomimetic Ocean, Avinent Implant System, Santpedor, Spain), with Three different implant-abutment connection designs and body diameters of the implants were 3.5 mm and the total body length was 10 mm, all the implant were subjected to a static compressive load ,they found that 20 control specimens (83.3%) fractured through the abutment screw, while four specimens (50%) represent a platform deformation, cervical rupture, implant body and abutment folding.

Examination the fracture surfaces of fractured dental implant and implant component is the optimal process to evaluate the causes and mechanisms of fracture as well as the presence of impurities, deformation, cracks, or fissures, which is based on scanning electron fractographic analysis (SEM) [24].

In the present research, the digital images obtained from fractographic analysis (SEM) were recorded at various magnifications to evaluate the distorted and fracture surfaces. The SEM reveals the damage caused by the compression test, with deformation on the implant fixture displaying compression on one side of the implant platform, with the formations of a gap on the opposite side. The implants failed on the bending side of the platform, with the fracture developing gradually in the apical direction along the implant body as the abutment screw was bent [24].

When metals undergo continuous plastic deformation, they finally fracture, and broken surfaces of implants exhibit two distinct characteristics: ductile and brittle. Ductile fractures often have a rough facet comprised of dimples, while brittle fractures exhibit less plastic deformation and exhibit a smooth, flat facet [25]. In the current study, implant wall and abutment fracture started with a slowdown ductile fracture with dimples and micro-voids and ended with quick fractures as shown by the shiny surfaces. These SEM results corroborate those published by Apicella and Chan *et al.,* [26]. Similarly, the failure mechanism of abutment screws was determined to be ductile, as shown by rough and dull surfaces with many big dimples. Due to the angle at which the two facets of the circular abutment screw fracture met, their union showed as a rung in the SEM pictures. The abutment screw had a tiny diameter of 2.0 mm and broke at stresses much less than those applied to the implant wall [27].

The fractures were oblique in nature, resulting in significant plastic distortion of the implant body and platform. Cracks began to appear at the implant platform and progressed apically down the implant body. The mismatch (gap) between the coils of the screw and the internal coils of the implant may have occurred as a result of the fixture diameter expanding in the direction of the applied load and screw movement in the vertical direction. However, the physics behind such observable occurrences may be better understood using finite-element simulations [22].

As with any in vitro study, the current study has numerous limitations. On the first hand, dental implant clinically is subjected to more dynamic masticatory forces in a biological environment with saliva, which is considerably different from conditions simulated in our experimental models that subjected only to static test. On the second hand, the selections of implant of the same company, but at the same time, all this implant has different thread shapes, that provide a wide evaluation and expectation for the clinician. However, it is very importance for the clinician to know the limitations of the products that will be used in their patients [3].

The findings of this study are significant for implant design and manufacturing experts. Additionally, they are beneficial to clinicians. According to Allum *et al.,* [28], the majority of dental implant manufacturers hide information on the mechanical strength of their implants, making it mainly inaccessible to clinical practitioners. Thus, the findings of this research dismantle obstacles and provide a basis for selecting between various implant threads when increased implant strength is desired to resist greater masticatory forces. Additionally, clinicians may utilize the data gathered during this study to form an opinion on the mechanical characteristics of implants as stated by manufacturers, who may overstate their products mechanical properties for commercial gain. However, clinical trials are crucial to validate the results of these investigations as well as those of the present in vitro study.

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