Impact of dental implant diameter on the efficiency of fatigue: A systematic review analysis

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Abstract

Objective: To explain the success and failure of dental implant diameter on the efficiency of fatigue.

Methods: The systematic review was conducted using PubMed and Cochrane databases for Original Articles published in the English language from 1999 to 2019. Outcomes were evaluated to determine perceptions regarding the role of dental implant diameter in influencing the implant's fatigue performance. Data was analysed using SPSS 22.

Results: Of the 263 abstracts retrieved, 53(20%) were reviewed. Of them, 14(26.4%) were included; 9(64.3%) systematic reviews, and 5(35.7%) studies. The implant diameter could be categorised into wide diameter (5-6mm), regular diameter (3.75-4mm), and small/narrow diameter (3-3.4mm). The narrow diameter implants are indicated through thin alveolar ridges and mesiodistal spaces (<7mm). The implants with narrow diameter would offer greater risk of fatigue failure for clinical situations with significant functional loading ($p<0.05$). No significant differences were found either in success or failure of dental implant diameter on fatigue efficiency at 1-year and 3-year follow-ups ($p>0.05$).

Conclusion: The technical complication of dental implant included abutment screw loosening or fracture, abutment and superstructure fracture, and implant body fracture. The review mainly focussed on the impact of dental implant diameter on the efficiency of fatigue and reviewed a significant impact of dental implant diameter on the fatigue efficiency.

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Introduction

In recent years, there has been an increase in the use of dental implants to treat either partial or complete edentulism within clinical settings.[1] Typically, dental implant designs are classified into four primary categories of interest; endosseous, ramus, blade and subperiosteal.[2] There have been many recent developments in implant prosthesis design, such as the use of titanium (Ti) to reinforce properties of strength and fatigue behaviour.[1] As a result, there is a wide variety of dental implants that are designed to effectively manage dental complications.

It is necessary to take appropriate care while designing dental implants, since tooth loss is a common occurrence globally.[3] In this regard, mechanical characteristics of dental implants are likely to be considered due to their fatigue behaviour. It is possible for the implants to face fracture under extensive physiological or biomechanical loading conditions.[1] Such loading conditions may occur due to para-functional habits and unsuitable implant designs. However, the failure is further exacerbated due to bone resorption around the implant. Thus, it is important to address the causal factors attributed to implant fracture and accordingly modify implant designs so that chances of failure decrease. The decrease in failure seeks to counter the detrimental issues faced by mechanical failure and fatigue in these implants.[4] Consequently, a longer implant life may be assured, leading to a significantly improved quality of life for the dental patient facing partial or complete edentulism.

One of the previous studies highlighted implant diameter to be a significant cause of implant failure and fracture.[5] These studies have suggested that narrow diameters had a significantly detrimental effect on the fatigue behaviour of the implant under consideration.[1] In this regard, the use of implants with larger diameters was recommended to enable the provision of a larger metal bulk. In this way, the applied stresses and loading may be reduced since the strength of implant is increased.[1] This highlighted the disadvantageous influence of narrow diameters and sharp notches in lowering the fatigue properties of dental implants.[1] Therefore, it is clear that the role of implant diameter is significant in terms of ascertaining the causal factors, resulting in implant failure. In this regard, it is essential that implant diameter should be taken into serious consideration when designing dental prosthesis so that potential failure may be avoided. The present systematic review aims at explaining the impact of dental implant diameter on the efficiency of fatigue due to lack of extensive literature surrounding the impact of implant diameter on the efficiency of fatigue. The findings from these studies would help to enable a deeper

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understanding of the significance of dental implant diameters.

It becomes essential to review the factors that lead to the success and failure of dental implant diameter. Implant survival, prosthetic outcomes, patient's subjective assessment, and peri-implant soft tissue are considered success parameters. However, mechanical failures, inappropriate patient adaptation, iatrogenic failures, and biological failures are considered failures to dental implant diameter. A disruption to the initial healing process is resulted due to early failures, which cause development of fibrous scar tissue between the surrounding bone and implant surface. In particular, the down-growth of epithelium is facilitated through this disruption. The loss of osseo-integration is evidently reported either radiographically or implant mobility as a peri-implant radiolucency, which is unable to significantly contribute to the functional ability of the bone-implant unit.

Materials and Methods

The systematic review was conducted using PubMed and Cochrane databases for Original Articles published in the English language from 1999 to 2019. The search was carried out based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (http://www.prisma-statement.org/PRISMAStatement/Default.aspx). Data collected was from the 'Journal of the Mechanical Behaviour of Biomedical Materials', 'Journal of Medical Devices', Applied Bionics and Biomechanics', BioMed Research International, 'Clinical Oral Implants Research', 'Dentistry Journal', and 'Dental Materials, Fatigue and Fracture of Engineering Materials and Structures'.

The articles included were Original Articles conducted prospectively or retrospectively. All other categories were excluded. Screening of all articles highlighting or discussing the success and failure of dental implant diameter on fatigue efficiency was done before their inclusion. The specific key words used for searching were 'dental implant', 'diameter', 'fatigue', 'failure', 'fracture', 'mechanical properties', and 'performance'.

The complete review process was regulated in two stages. Initially, the evaluation of every abstract was carried out by the investigator. In this regard, solely those abstracts that directly discussed an association between dental implant diameter and fatigue behaviour were included. Therefore, a major exclusion took place in the first phase. Rest of the articles were evaluated again in the second phase where abstracts were selected by the investigator and academic professional for a deeper analysis and review. Articles data that was relatively less reliable were discarded. The outcomes from these studies were evaluated to determine their perceptions regarding the role of dental implant diameter in influencing the implant's fatigue performance (Figure 1).

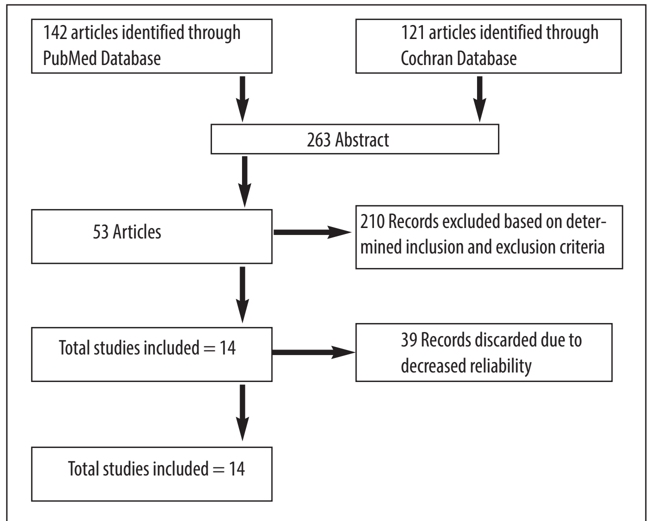

Figure-1: Study flow chart.

Data was analysed using SPSS 22. Weighted Cohen's Kappa was used to report the inter-observer agreement with respect to reporting of experimental studies prior to their inclusion. Means and standard deviations (SD), interquartile ranges (IQRs), and medians were used to express descriptive statistics. RevMan software was used for Forrest plot, Funnel plot, and for calculating odds ratio (ORs) with confidence interval (CI). P<0.05 was considered statistically significant.

Results

Study Characteristics: Of the 263 abstracts retrieved, 53(20%) were reviewed. Of them, 14(26.4%) were included; 9(64.3%) systematic reviews, and 5(35.7%) studies for meta-analyses (Table 1). Major reasons for including a small number of studies in meta-analysis were that majority of the studies had inadequate description of study, analysis was duplicate across different publications, and inadequate

Table-1: The studies included in the systematic review.

Study	Type	Country	Implant System	Sample
Quek et al.[6]	Experimental study	Singapore	Abutment	5 implants
Scheidel et al.[7]	Experimental study	Japan	Titanium	10 implants
Ilies et al.[8]	Experimental study	United States	Subperiosteal	9 implants
Prados-Privado et al.[9]	Experimental study	Spain	Conical	2 implants
Prados-Privado et al.[10]	Observational study	Spain	Cylindrical and conical	2 implants
Duan and Griggs[11]	Experimental study	United States	Titanium	36 implants
Elias et al.[12]	Observational study	Brazil	Screw-shape	255
Fan et al.[13]	Experimental study	China	Regular and narrow	3
Shemtov-Yona et al.[1]	Experimental study	Israel	Static	15
Bordin et al.[14]	Experimental study	Brazil	Narrow	42

explanation of impact of dental implant diameter on the efficiency of fatigue .

Qualitative Synthesis: Based on the review analysis, there was a significant impact of dental implant diameter on the fatigue efficiency. A brief analysis of the studies included was generated (Table 2). The three categories of implant diameter were wide diameter (5-6mm), regular diameter (3.75-4 mm), and small/narrow diameter (3-3.4 mm). The thin alveolar ridges and mesiodistal spaces (<7mm) indicated narrow diameter implants. A study[6] on the fatigue performance of wide, regular and narrow implants and abutments tested implant-abutment combination of 5 samples for three different widths through the application of different levels of torque. The results presented no failure in the wide-diameter implants. Moreover, the abutment screw was not only the potential failure location. Therefore, it can be stated that the implants with narrow diameter would offer greater risk of fatigue failure for clinical situations with significant functional loading.[6]

Scheidel et al.[7] investigated the impact of shear fatigue strength using self-etch adhesive systems, and showed that the same shear fatigue strength was found among the adhesives at frequencies of 1, 10 and 20Hz. Therefore, it can be stated that frequencies >20Hz is needed for expediting fatigue testing of dentin binds using self-etch adhesives.

Ilies et al.[8] developed a finite element-based fatigue model with both physical measurements and analytical predictions for rigidly mounted dental implants. This system shows its validity in predicting fatigue life of dental implants and its significance as an implant design instrument.

Prados-Privado et al.[9] investigated two different dental implants by simulating a model with a force of 489N and angles of 0º, 15º, and 20º. The study evaluated the Von Mises stress distribution by using the probability cumulative function and the statistic of the fatigue life function. This function enabled the study to consider each life-cycle with failure probability. Under the same loading force, cylindrical implant haf an adverse behaviour compared to the conical implant investigated.

Prados-Privado et al.[10] in another study predicted the maximum principal stress for internal connection 39 MPa and external connection 32 MPa in the trabecular and cortical bone, respectively. For external and internal connection, a mean life of 103 and 210 million cycles, respectively, was suggested. The study assessed probability cumulative function for both connection conditions. A cumulative damage model and probabilistic finite element method were employed within this stochastic model.

Duan and Griggs[11] found a significant negative influence on the fatigue lifetime for the load amplitude of the regression model term. The load-frequency interaction and the cyclic frequency term were not substantially different

Table-2: Overview of the included studies.

Study	Methods	Significant Outcome
Quek et al.[6]	Use of rotational load fatigue machine towards the long axis of the specimen.	Superior load fatigue performance was demonstrated by the wide-diameter CeraOne single tooth implant system.
Scheidel et al.[7]	Self-etch adhesive systems was used to determine shear fatigue strength of resin composite bonded to dentin.	No significant difference in bond failure mode among different frequency rates of the three adhesives.
Ilies et al.[8]	A finite element based fatigue model was developed for dental implants that are mountly rigidly.	A device was presented for measuring fatigue life of dental implants predicted by the finite element model.
Prados-Privado et al.[9]	Dental implants were subjected to masticatory force of 118 N in the angle of 75° to the occlusal plane.	As compared to the external hexagon, internal connection is more effective on the distributing loads.
Prados-Privado et al.[10]	Fatigue analysis was explained from a probabilistic point of view, based on a cumulative damage model and probabilistic finite elements.	Under bruxism condition, all the stresses in the benchmark are bigger.
Duan and Griggs[11]	Assembling of 36 titanium dental implant specimens was done following the apparatus specified by the ISO 14801 test standard.	The efficiency of fatigue testing is likely to be improved as the result of higher loading frequency.
Elias et al.[12]	Static and dynamic compressive loads were subjected to machined screw-shaped implants with three different designs.	The track initiation is likely to be delayed as the result of increased fatigue strength of the nanocrystalline Ti G4.
Fan et al.[13]	Cyclic compression and static loading were used to test three groups of different diameter implants under stimulated physiological environment conditions.	Wide diameter implants are likely to withstand greater load.
Shemtov-Yona et al.[1]	Static and cyclic compressive conditions were implemented to test the implants with different diameters (3.3 mm, 3.75 mm and 5 mm).	Typical fatigue behaviour was not shown by the narrow implants.
Bordin et al.[16]	42 implants were tested for macro geometry and internal conical connection.	Considering the probability of survival, there was no significant difference between narrow and extra-narrow implants.

from zero, which revealed that augmenting loading frequency did not affect the number of failure cycles.

Elias et al.[12] compared the fatigue failure and compressive strength of dental implants by using Equal Channel Angular Pressing (ECAP) with a conventional material. Higher static compressive strength was shown by implants made with Ti Hard compared to implants made with commercially pure titanium (TiG4).

Fan et al.[13] revealed that the ability of implant loading can be influenced by the implant diameter to explain superior load fatigue performance with a wider diameter. A typical fatigue behaviour was revealed from the narrow group that indicates a fracture risk in clinical practice for classifying the implant design.

Bordin et al.[14] revealed a reduced reliability for both extra-narrow and narrow dental implants at 180N and 150N. The results further indicated a dominant failure in abutment fracture for both implant types. Higher von-Misses stress was shown for implant and abutment at 50N load
(Table 2).

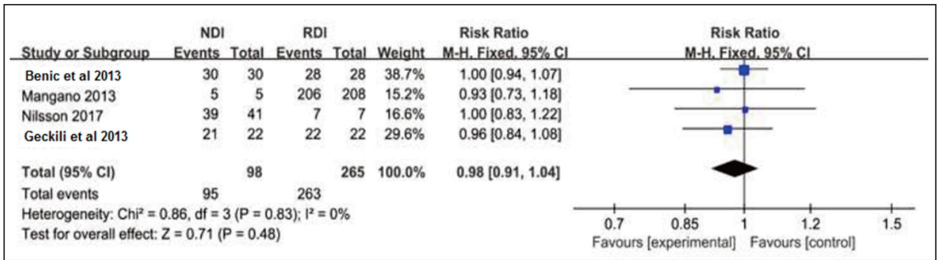

Figure-2: One-year implant success rates in both groups (Forrest Plot).

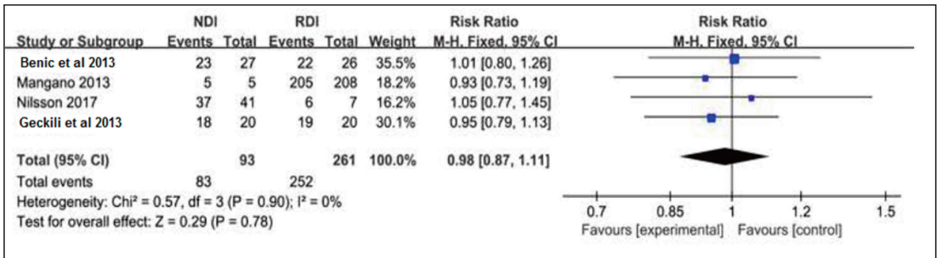

Figure-3: Three-year implant success rates in both groups (Forrest Plot).

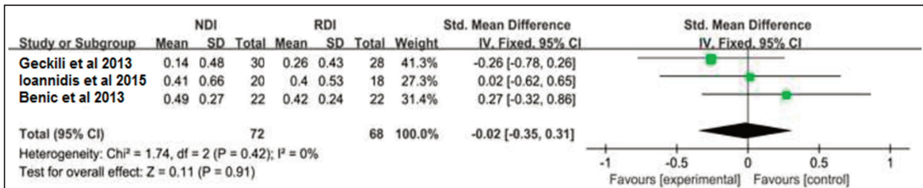

Figure-4: One-year implant failure rates in both groups (Forrest Plot).

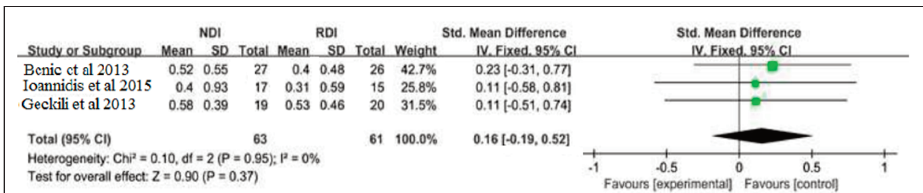

Figure-5: Three-year implant failure rates in both groups (Forrest Plot).

Comparison of the implant success rates at 1-year follow-up: The 1-year success rates for dental implant diameter were evaluated by 4 studies.[15-18] No heterogeneities were found in groups. The subsequent values were 99.25% and 96.94% for regular diameter implants and narrow diameter implants, respectively, for 1-year fatigue success rates. The study also found lower success rates for fatigue treatment at 1-year in narrow diameter implant group compared to regular diameter implant group (p=0.023) (Figure 2).

Comparison of the implant success rates at 3-year follow-up: The three-year follow-up analysis was based on the fixed effects model and revealed no heterogeneities in groups.[15-18] The subsequent values were 96.55% for regular diameter implants, and 89.25% for narrow diameter implants at 3 years. Similarly, there were lower success rates for narrow diameter implants compared to regular diameter implants at 3 years (Figure 3).

Comparison of the implant failure rates at 1-year follow-up: Three studies[15,18,19] were selected to compare the 1-year outcome between regular diameter and narrow diameter implants on fatigue efficiency. No heterogeneities were identified in both the groups, and the analysis was based on fixed-effects model from which the 1-year failure rates for narrow diameter implants was similar to regular diameter implant groups (Figure 4)

Comparison of the implant failure rates at 3-year follow-up: Evaluation of 3-year outcome between regular diameter and narrow diameter implants on fatigue efficiency was also done.[15,18,19] No heterogeneities were identified in both the groups. The analysis was based on fixed-effects model from which the 3-year failure rates for narrow diameter implants was similar to regular diameter implant groups (Figure 5).

Discussion

The success of dental implant depends on a wide variety of factors although it has emerged as a feasible and popular treatment option among patients with the need of removable prostheses. There is no doubt about the fact that information on functional life of an implant is considered the most important therapeutic parameter for prosthetic longevity. The steps towards development of finite element on the basis of fatigue model mounted on dental implants were presented by Ilies et al.[8] The results presented in this study correlated with the physical measurements and the analytical predictions. Further, it was suggested that finite element models of fatigue could be utilised as reasonable predictors of the actual fatigue life of the dental implants. These results have been presented in the context of influence on the fatigue life of dental implants and behaviour of the bone itself.

There is a significant influence of loading type, implant surface, implant geometry, and quality and quantity of surrounding bone on the load transfer from implants. A wide variety of studies have helped in understanding the mechanism of load transfer to the bone from the implants. In the similar context, a study[9] focussed on the fatigue life of two different connections of a dental implant as the load is transferred to the bone. The study employed two dental implants. Considering the variability of loads and Young's modulus, the study applied probabilistic methodology for the Ti dental implants. Loads could not be considered deterministic due to uncertainty between bite habits of different individuals. The results clarified that internal connection plays an important role in distributing loads compared to the external hexagon for the coarse trabecular bone (D2) type bone.[9]

The use of dental implants has become an everyday practice, but the prosthetic implant failure occurs as the result of biological and mechanical causes. Infection, osseo-integration, and impaired healing are considered the primary causes that lead to implant failure. The dental implants made of Ti (alloy or pure) are considered highly compatible as they exhibit outstanding balance between the physiochemical, biofunctional, and mechanical properties. a study[10] mainly focused on fatigue analysis and a new method of studying fatigue was explained based on a cumulative damage model and probabilistic finite elements. The study showed that there was variability in the behaviour of implants because there was no consistency in the masticatory forces and there might be difference in the material properties along with the implants. Two different load magnitudes, masticatory load and bruxism, were evaluated for the pro-clinic dental implant, which showed that the cylindrical implants possess greater uncertainty in the fatigue process.[10]

In recent decades, there is an increase in the predictability of endosseous oral implant designs for clinical use. However, geometry and volume of alveolar bone may restrict the regions of mandible and maxilla. In these cases, surgical modification in the anatomy of the patients is required through alveolar distraction or inferior alveolar nerve transposition and bone grafting techniques that would allow the placement of longer and wider implants. The restrictions have been advocated towards the placement of bone considering its volume and height, and this is despite the increased success rates of endosseous oral implants. A systematic review explored the association between the survival rates of implant along with their length and diameter covering the period of 1990-2005.[11] The analysis showed that the choice of short or wide implant played an important role in the success of tooth implant as it was associated with any previous injury, trauma and bone resorption.

The occurrence of fracture is common among dental implants because of certain mechanical failures. Therefore, there is a need to study fatigue failure, its identification, along with its performance during service. A study[12] focussed the concept of dental implant fatigue to understand the mechanism of failure. The review study emphasised on the state of the art, current limitations, and open issues in line with the issue of fatigue failure of dental implants. It is difficult to devise the average representative value for characterising the environment and service conditions of dental implants. Similar to the application of random spectrum loading in aeronautics and earthquake engineering, there is a need to consider and characterise the certification of dental implants.

Another study investigated the impact of loading frequency on the lifetime fatigue of standard-diameter Ti dental implant system. For this purpose, a total of 36 specimens of Ti dental implants were assembled and moment arm of 11 mm was used for bonding stainless steel loading hemispheres on the abutments. These abutments were subjected to constant-stress fatigue lifetime testing and examination of the fractured specimens was conducted using fractographic technique to determine the failure mode. The results exhibited identical combined fracture of abutment and abutment screw adjacent to the bone level. Therefore, it can be concluded that the efficacy of fatigue testing can be improved through higher load frequency of approximately 15Hz to be used in the implant systems.

The need of improving the surface quality of dental implants has been highlighted although, there is no change in the materials being utilised for manufacturing the implants. It is important to make appropriate choice for the material implant after checking its biocompatibility and mechanical strength. The esthetical and functional recovery is compromised because of fracture of any implant component, hindering the long-term performance of the implants. In the similar context, the compressive strength and fatigue failure of dental implant were compared with three different designs by Elias et al.[14] The results depicted that collapse of the components mainly occurred in the body of implant, which is important for patient rehabilitation. From the clinical perspective, the breaking of implant body makes the implant failure more catastrophic. Moreover, a serious problem may arise as the result of implant fracture.

The implant fracture due to fatigue is aggravated by bone resorption under physiological load, as the osseo-integration was compared to experimental fractures produced by overload. Fan et al.[15] investigated the impact of diameter on the mechanical properties and load fatigue of the dental implants. Narrow, regular, and wide diameters of dental implants were considered in two different environments. The results demonstrated that the ability to withstand loading is likely to be affected based on the diameter on implants. For instance, superior load fatigue performance is demonstrated through the presence of wider diameter of dental implant. Moreover, a typical fatigue behaviour was shown by the individuals placed with narrow implants, which indicated increased risk of fracture attributed to the implant design.

The appearance of repeated loads is known as the potent cause of failure of dental implants. Therefore, there is a need to evaluate the fatigue performance for different diameters via constructing S-N curves. A study[1] showed a significant impact of diameter on the fatigue performance of different implants. For instance, classic comparable fatigue behaviour was exhibited by 5mm and 3.75 mm implants; whereas, the 3.3 mm implant did not exhibit typical fatigue behaviour. These results indicated the need of detailed fracture mode analysis for identifying the probable cause of observed fatigue behaviour.

Fatigue testing of narrow dental implants is important for understanding the survival and failure of the implant-abutment-prostheses system, considering the fact that strength degradation of systems in function hampers their mechanical performance. Bordin et al.[16] assessed the probability of failure modes of narrow implants, exhibiting different diameters. For this purpose, two virtual methods were considered that stimulate the samples tested for fatigue. The results considering the probability of survival showed no significant differences between narrow and extra-narrow diameters. There would be no difference in the narrow and extra-narrow implant diameter considering the difference in reliability and failure mode.

A total of 5 studies[15-19] were included in the meta-analysis for evaluating the success and failure of dental implant diameters on fatigue efficiency based on regular and narrow diameter implant groups. The 1-year and 3-year diameter implant success rates were documented in four studies[16-19] with three dental implants, and found no significant difference between regular diameter implants and narrow diameter implants with respect to fatigue efficiency. Similarly, three studies evaluated the failure of dental implant diameters on fatigue efficiency, and found no significant differences.[15-17] However, both groups have shown similar failure rates at 1-year and 3-year follow-up.

Future studies should examine the same parameters with the purpose of acquiring additional clinically-appropriate information. However, the heterogeneity of such articles develops doubt in the field of dentistry in scientific literature. Thereby, future in-vitro analyses should comprise the same dimensions (diameter) and cyclic loading conditions with respect to the findings obtained in the current systematic review. It is essential for standardising the criteria to conduct studies for making appropriate and concise comparisons based on the identified homogeneity in the selected studies.

Conclusion

Dental implants have been used as an effective method for replacing missing teeth that improves quality of life of individuals. Abutment screw loosening or fracture, abutment and superstructure fracture, and implant body fracture are considered technical complications of dental implants. The present study mainly focussed on the impact of dental implant diameter on the efficiency of fatigue by conducting a systematic review analysis. The study has provided deep understanding regarding the significance of dental implant diameters. There are three distinct stages that manifest the fatigue failure, such as microscopic cracks in the area of stress concentration initiated from the small imperfections, sub-critical crack growth, and, finally, catastrophic failure reaching the critical stress intensity factor after a crack. Frequent technical complications are observed in late failures, but there is a rare observation of these complications in early implant failures.

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