The Prosthetic Influence and Biomechanics on Peri-Implant Strain: a Systematic Literature Review of Finite Element Studies

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ABSTRACT

Objectives: To systematically review risks of mechanical impact on peri-implant strain and prosthetic influence on stability across finite element studies.
Material and Methods: An online literature search was performed on MEDLINE and EMBASE databases published between 2011 and 2016. Following keywords tiered screening and selection of the title, abstract and full-text were performed. Studies of finite element analysis (FEA) were considered for inclusion that were written in English and revealed stress concentrations or strain at peri-implant bone level.
Results: There were included 20 FEA studies in total. Data were organized according to the following topics: bone layers, type of bone, osseointegration level, bone level, design of implant, diameter and length of implant, implant-abutment connection, type of supra-construction, loading axis, measurement units. The stress or strain at implant-bone contact was measured over all studies and numerical values estimated. Risks of overloading were accented as non-axial loading, misfits, cantilevers and the stability of peri-implant bone was related with the usage of platform switch connection of abutment.
Conclusions: Peri-implant area could be affected by non-axial loading, cantilever prosthetic elements, crown/implant ratio, type of implant-abutment connection, misfits, properties of restoration materials and antagonistic tooth. The heterogeneity of finite element analysis studies limits systematization of data. Results of these studies are comparable with other findings of *in vitro*, *in vivo*, prospective and retrospective studies.

Keywords: dental implants; dental stress analysis; finite element analysis; peri-implantitis; treatment failure.

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INTRODUCTION

Contemporary restorations of dental defects with implants are widely applicable, clinically prospective and comfortable treatment method. Although it is important to realize that this method, as all other restorative procedures, is aimed not to change the tooth but exactly restore what has been lost in biological and mechanical aspects [1,2].
An implant success rate is a numerical quantitative expression, which values the success of the implant as a matter of persistence until its fatal loss. This rate reaches 95% and is based on the osseointegration of the implant [3]. If the osseointegration does not occur, the implant will be rejected and will not have a successful outcome because of early complications. There are two types of failures: early complication, which occur before the prosthetics and late complications after osseointegration and restoration [2,4-8]. It means that all 95% of successful implants still have risks of late failures, which are related with longevity and quality of treatment. Under functional loading condition physiologically we can expect 1 - 1.5 mm bone loss throughout the first year and < 0.2 mm every following year [8,9]. This process could be accelerated by mechanical, chemical and biological factors. With lack of attention and control, this physiological process may turn into a pathological inflammation of peri-implant soft tissues as peri-implant mucositis or its later form: peri-implantitis.
Despite high implant survival rate, epidemiological studies and clinicians insufficiently paying attention to the quality factor and sustainability of our final restoration. However, there should be understood that implants cannot sufficiently replace natural teeth despite their survival rates [2].
Some of the main reasons for late implant failures can be bacterial factors, host health conditions (diabetes mellitus and bisphosphonates), smoking, overloading and iatrogenic factors [9-11]. Overloading and iatrogenic risk factors are closely related with prosthetic solutions.
Major debates and the absence of consensus prevail especially due to overloading effect on implant complications. The intact root of the tooth is covered by periodontium and has 25 to 100 µm micro-movements on axial direction. In comparison, osseointegrated dental implants can move just 3 to 5 µm at the same axis [12,13]. Tooth mobility is determined by deformation of periodontal ligaments while implant mobility is determined by limited deformation of the bone. In a micro-movement like this, the periodontal ligament works as a damper and can reduce the effect of the stress on surrounding structures. Moreover, periodontium could adjust the load because of proprioceptive sensors. According to mechanostat theory by Frost [14], both bone growth and resorption are closely dependent on affecting mechanical forces. So the osseointegrated implant can be overloaded and not survive due to loading [15]. However, there are no clear guidelines: how much functional and para-functional loading can be injurious for dental implant, what mechanical factors can decrease load effect for such kind of restorations and what should be avoided. These are still not reviewed in older publications.
The aim of this review is to find out risks of mechanical impacts of peri-implant bone loss and prosthetic influence on bone stability.

MATERIAL AND METHODS

Protocol and registration

The review was registered on the international prospective register of systematic reviews PROSPERO. Registration number: CRD42016037224. The design of data search, analysis and selection criteria was described in advance. This protocol could be found in PROSPERO register:
http://www.crd.york.ac.uk/PROSPERO/display_record.asp?ID=CRD42016037224
This review was performed following PRISMA statements (Preferred Reporting Item for Systematic Review and Meta-Analyses) [16].

Types of publications

The review included publications in English, which were published from January 2011 till April 2016. Letters, editorials, literature reviews, PhD theses and abstracts were excluded.

Types of studies

The selection of studies consists of randomized control trials, cohort studies, case-control studies, case reports, animal and *in vitro* studies.

Information sources and search

A literature search was performed of two databases - MEDLINE (PubMed) and EMBASE websites. The specific keywords were selected on purpose to establish a maximal informative and an accurate search. Keywords were as follows: “absorbing”, "bone", "damping", "dental implant", "disintegration", "loss", "occlusal", "overloading", "peri-implant", "shock", "strain", "stress". According to these, the search was performed on PubMed and EMBASE search systems: "dental" AND "implant" AND ("overloading" OR "stress" OR "shock" OR "strain") AND (("bone" AND "loss") OR "disintegration" OR "damping" OR "absorbing").

Selection of studies

Two reviewers independently screened the title and abstract of articles derived from this broad search. After primary screening decisions of both reviewers were compared and discussed. The third experienced reviewer accomplished a secondary screening for those cases where the disagreement was.

Inclusion criteria

The inclusion of articles was done according to: the description of the usage of dental implants, the estimation of implant loading, the load transmission and distribution over peri-implant bone or bone level changes. Fixed prosthetic treatment and functional loading or over-loading should be applied in studies.

Exclusion criteria

In order to review the latest data, the studies over 5 years old were not included. 3 studies were excluded because they lacked an abstract. Studies which evaluated removable dentures on implants were excluded. The biomechanical functionality of such prostheses is different than fixed. Also, studies that analyse the effect of masticatory forces in restoration level only (crown, abutment, screw) without changes in the bone level were excluded.

Data extraction

The selected studies were divided into groups according to the type of the study: experimental *in vitro*, experimental *in vivo* and clinical. Data of experimental finite element analysis (FEA) studies were systematized in assessing load vector and value, stress and strain in peri-implant bone, implant length, diameter, bone layers, type of bone, bone level, osseointegration level, implant design, type of implant-abutment connection, restoration (Table 1).

Data items

Data were collected from the included FEA studies and arranged in the following fields:

- "Bone layers" - shows types of applied bone layers;
- "Type of bone" - describes the density of bone;
- "Osseointegration level" – characterizes the conditions of implant osseointegration;
- "Bone level" - describes the depth of implant position;
- "Design of implant" - describes the shape of implant model;
- "Diameter of implant" - describes diameter dimension;
- "Length of implant" - describes length dimension;
- "Implant-abutment connection" - shows type of connection (platform switch or non-platform switch);
- "Type of supra-construction" - description of prosthesis;
- "Axial load" - strength value in an axial direction;
- "Oblique load" - strength value in an oblique direction;
- "Lateral load" - strength value in a lateral direction;
- "Stress/strain units" - measuring units.

Assessment of methodological quality

The intrinsic methodological and lacks of design were independently screened by two reviewers. The qualitative assessment was accomplished for each of elected study and their risk of bias was evaluated according to the Cochrane library [17].

RESULTS

Study selection

The search on MEDLINE (PubMed) and EMBASE databases resulted in 533 publications. Following inclusion/exclusion criteria 42 articles were selected and fully read. They were grouped according to the type of the study: 20 - *in vitro* FEA; 8 - *in vitro* (tests); 5 - *in vivo*; 3 - prospective, 6 - retrospective. The distribution of publications shows the prevalence of virtual FEA mechanistic studies. With the intention of achieving methodical homogeneity, FEA studies were selected for a detailed analysis and comparison of results and values. All FEA studies (n = 20) were involved in data analysis (Figure 1).

Study characteristics

The analysis of articles, which describes the FEA study, illustrates that both conditions and the obtained data are heterogeneous (Table 1).

Table 1. Collected data

Study	Year of publication	Bone layers	Type of bone	Osseo integration level	Bone level (mm)	Design of implant	Diameter of implant (mm)	Length of implant (mm)	Implant-abutment connection	Type of supra construction	Axial load	Oblique load	Lateral load	Stress/strain units
Jimbo et al. [18]	2013	C	ND	Medium/partial	ND	Cylindrical	ND	ND	PS	NA	250 N; 200 N	NA	NA	MPa
Aguirrebeitia et al. [19]	2013	C	ND	High/full	ND	Threaded	4.5	9	PS	Abutment	NA	200 N; 30°	NA	von Mises MPa
Bouazza-Juanes et al. [20]	2015	C+T	ND	High/full	0	Threaded	4.1	11	NPS; PS	NA	100 N	100 N; 15°	NA	von Mises MPa
Sahabi et al. [21]	2013	C+T	ND	High/full	0	Threaded	3.5; 4; 4.8; 5	11; 11.5	NPS; PS	NA	100 N	100 N; 15°	NA	von Mises MPa
Paul et al. [22]	2013	C+T	D3	Medium/partial	0	Threaded	4.3	13	NPS; PS	NA	50 N; 150 N; 250 N	50 N; 150 N; 250 N; 45°	NA	µStrain
Martini et al. [23]	2012	C+T	ND	High/full	ND	Threaded	5	13	PS	Ceramic	100 N	100 N; 45°	NA	MPa
Vidya et al. [24]	2014	C+T	D2	High/full	0	ND	4.3	6; 8; 10; 13	One-piece	NA	250 N	ND	100 N	von Mises MPa
I-Chiang et al. [25]	2014	C+T	D4	Absent; high/full	0.5	Threaded	3.7; 4; 4.1	11	NA	NA	300 N; 460 N	150 N; 60°	75 N	von Mises MPa
Santiago Junior et al. [26]	2013	C+T	D3	ND	0	Threaded	3.75; 5	10	NPS	Ceramic; composite; acrylic; metal	200 N	100 N; ND	NA	MPa; von Mises MPa
Savadi et al. [27]	2011	C+T	ND	ND	ND	Cylindrical	4.1	12	ND	NA	100 N	NA	50 N	von Mises MPa
Chou I-C et al. [28]	2014	C+T	D4	Absent; high/full	0	Threaded	3.9; 4; 4.1	11	NA	NA	500 N	NA	NA	von Mises MPa
Demenko et al. [29]	2014	C+T	D1; D2; D3; D4	High/full	ND	Cylindrical	3; 3.5; 4; 4.5; 5	8; 10; 12; 14	NA	NA	NA	118.2 N; 75°	NA	von Mises MPa
Bölükbaşı et al. [30]	2015	C+T	D3	ND	ND	ND	3.3; 4.1	12	PS	Metal-ceramic	NA	100 N; 45°	NA	µStrain
Ormianer et al. [31]	2012	C+T	ND	Medium/partial; high/full	ND	Threaded	3.7; 4.7; 6	ND	ND	Titanium coping	NA	222 N; 30°	NA	von Mises MPa
Xia et al. [33]	2013	C+T	ND	High/full	0; -2	ND	ND	ND	NPS; PS	Metal	200 N	200 N; ND	NA	MPa
Sotto-Maior et al. [34]	2012	C+T	ND	ND	ND	Threaded	5	7	NPS	Gold-ceramic; zirconium-ceramic	200 N	NA	NA	von Mises MPa
Romeed et al. [36]	2013	C+T	ND	ND	-4.5; -3; -1.5; 0	ND	3.5	13	ND	ND	ND	ND	ND	von Mises MPa
Arun Kumar et al. [38]	2013	C+T	D1; D2; D3; D4	High/full	0	Threaded	4.3	10	NPS	NA	178 N	NA	NA	von Mises MPa
Alvarez-Arenal et al. [63]	2014	C+T	D2	High/full	ND	Threaded	ND	ND	ND	Metal-ceramic	NA	249.9 N; 6 - 35°	NA	von Mises MPa
Kurniawan et al. [64]	2012	C+T	D2; D3; D4	Low; medium/partial; high/full	0	Threaded	3.8	ND	ND	NA	380 N	NA	NA	MPa; µStrain

C = cortical bone; T = trabecular bone; D1, D2, D3, D4 = bone density rate; MPa = Megapascals; N = Newtons; NA = not appropriate; ND = no data; PS = platform switch; NPS = non-platform switch; µStrain = a common engineering unit measuring strain.

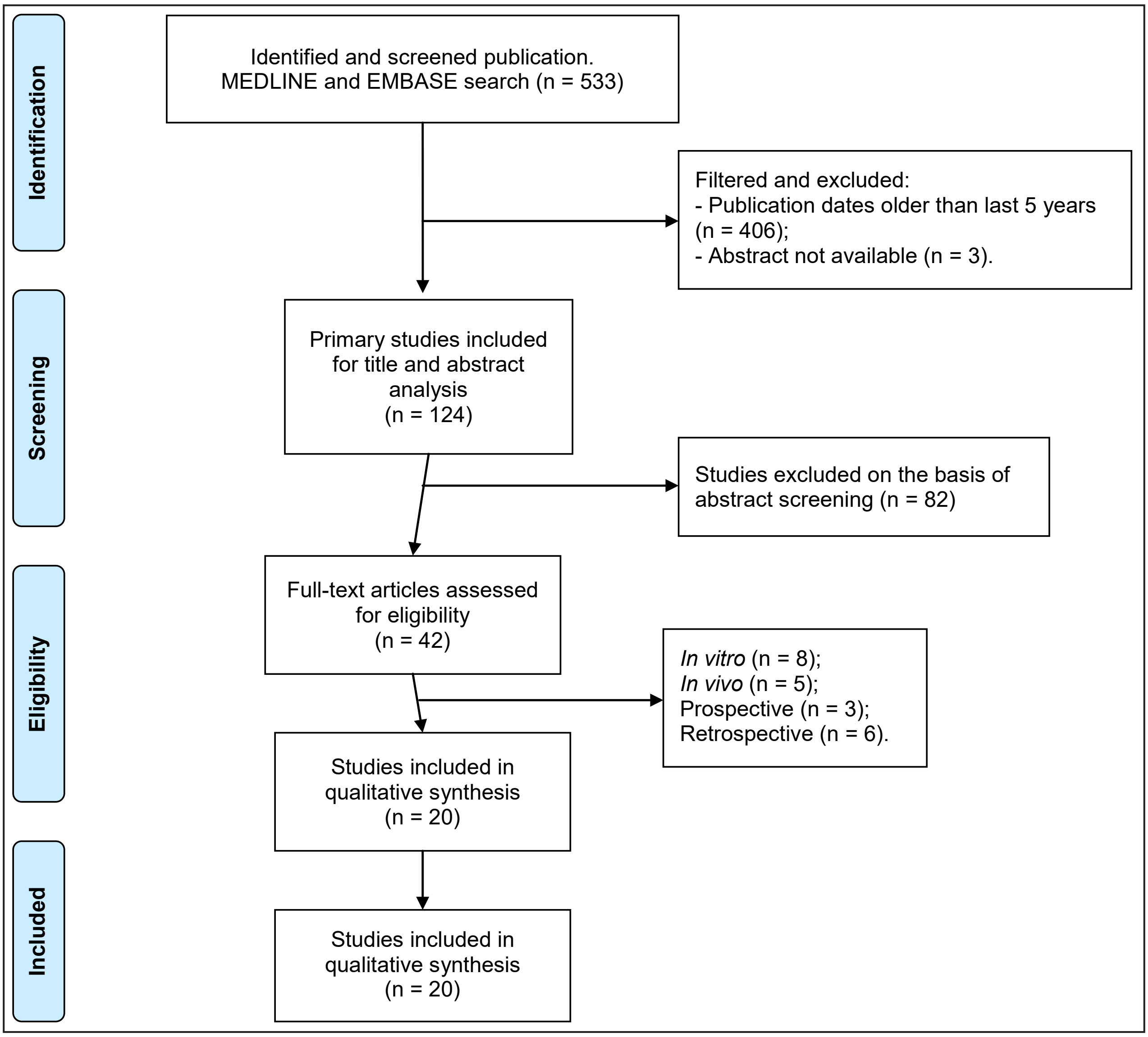

Figure 1. Procedural flow of the literature search and selection process.

According to methods, studies differ on the different simulated conditions:

1. A different bone base. Mainly, double layered (cortical + trabecular) bone model was applied and only a few models were single layered [18,19]. The authors programmed various bone types (D1 - D4) and some were evaluating stress distribution on bone following density. The shape of the bone model had variations too. For example, it could be programmed as a peri-implant cylinder, as a section of the jaw or a full dental arch. Some authors provided a real scanned situation.
2. A different osseointegration. In reality, implant is not fused with bone absolutely. There is no consensus for osseointegration conditions on FEA. Some referred to it as an ideal for simplicity (100% integration) and others as a partial osseointegration for more realistic model.
3. Variation of implants design. There were different selection of implant length, diameter, thread and other properties in the studies. There were studies, which defined a cohort according to the geometry.
4. Variation of the implant-abutment connection. Some of the investigations were carried out without a reference of the implant-abutment connection or completely without it. Others defined a cohort according to the connection type.
5. Different restorative solutions. The selection of restorative materials, layers, bonding conditions and shapes varied. Also, there were studies in which the investigation was performed only at implant-abutment model.
6. Different loading directions. Variable loading vectors were distributed as follows: axial, oblique and lateral. The angle of oblique load was a variable too. Some studies analysed stress distribution depending on load direction

but mostly dominated free of choice.

7. Loading variation. The loading conditions are simulated not only at different vectors but also at different loads, which were used from 50 to 500 N.
8. Different outcome units. The gained data were presented in different units of measurement. The dominant measuring of stress was expressed in *von Mises* MPa, but studies with tangential stress were measured in MPa or strain in µStrain.
9. There were certainly other differences among models that were less emphasized.
10. The impact of loading resulted in stress or strain at the implant-bone interface was described in all 20 publications. Mainly there were stress dependence on the force acting axis [20-28] and all authors assured that non-axial loading increased peri-implant stress. Also, implant design characteristics were described as factors causing the stress. The alteration of stress was related with implant length [21,24,29], width [21,25,26,28-31], macro-relief as thread [28,32], and micro-relief as porosity [27]. Some of the articles emphasized that stress changes were caused by platform switching connection [20-22,33]. The influence of abutment-implant connection was also described by another two articles, who revealed impact of inaccuracy at this interface [18,19]. Prosthetic related factors as crown/implant (C/I) ratio [34] and restorative materials [26,34] were also analysed.

Quality assessment

All the selected studies were assessed for their risk of bias according to the Cochrane library [17]. The sequence generation was not explained and moreover limited. The included studies did not report it. The sequence generation could be debatable for *in vitro* or perhaps impossible, especially for FEA. Evaluation of allocation concealment and blinding of participants and outcomes of *in vitro* studies was confirmed severe and not appropriate. The incomplete outcome data was not explained in most cases and assessment “unclear” means that no missing data was reported (Table 2).

Synthesis of results

Due to the study design and conditions, heterogeneity of outcomes may not achieve a comparison of results and statistical analysis. The collected data are ineligible for meta-analysis and/or systematic review.

Table 2. Bias summary

Study	Adequate sequence generation?	Allocation concealment?	Blinding of outcome assessment?	Incomplete outcome data addressed?	Free of selective reporting?	Free of other bias?
Jimbo et al. [18]	Unclear	NA	NA	Unclear	No	Yes
Aguirrebeitia et al. [19]	Unclear	NA	NA	Unclear	Yes	Yes
Bouazza-Juanes et al. [20]	Unclear	NA	NA	Unclear	Yes	Yes
Sahabi et al. [21]	Unclear	NA	NA	Unclear	Yes	Yes
Paul et al. [22]	Unclear	NA	NA	Unclear	Unclear	Yes
Martini et al. [23]	Unclear	NA	NA	Unclear	Yes	Yes
Vidya et al. [24]	Unclear	NA	NA	Unclear	Yes	Unclear
I-Chiang et al. [25]	Unclear	NA	NA	Unclear	Yes	Yes
Santiago Junior et al. [26]	Unclear	NA	NA	Unclear	Unclear	Unclear
Savadi et al. [27]	Unclear	NA	NA	No	Unclear	Yes
Chou I-C et al. [28]	Unclear	NA	NA	Unclear	Unclear	Yes
Demenko et al. [29]	Unclear	NA	NA	Unclear	Yes	Yes
Bölükbaşı et al. [30]	Unclear	NA	NA	Unclear	Yes	Yes
Ormianer et al. [31]	Unclear	NA	NA	No	Unclear	Unclear
Xia et al. [33]	Unclear	NA	NA	Unclear	Yes	Yes
Sotto-Maior et al. [34]	Unclear	NA	NA	Unclear	Yes	Yes
Romeed et al. [36]	Unclear	NA	NA	No	Unclear	Yes
Arun Kumar et al. [38]	Unclear	NA	NA	Unclear	Yes	Yes
Alvarez-Arenal et al. [63]	Unclear	NA	NA	Unclear	Unclear	Unclear
Kurniawan et al. [64]	Unclear	NA	NA	Unclear	Yes	Yes

NA = not appropriate.

DISCUSSION

This review was performed with an aim to systematically review risks of mechanical impact on peri-implant strain and prosthetic influence for stability across FEA studies. Despite the heterogeneity between the FEA studies, the established trends correlate with other *in vitro*, *in vivo*, prospective and retrospective studies from the same search.

According to Newton's third law it is undisputed that chewing forces are transmitted to restoration and these forces do not decrease but transform into energy, which is distributed in certain amounts through the restoration-implant complex. Energy could be distributed into restorative materials, cement layer, abutment, screw, implants and peri-implant bone. According to reviewed studies, an overloading of peri-implant bone could be determined by several factors.

FEA studies have shown dependence between stress distribution and loading direction [35]. Assessing the effect of the axial force, was detected the distribution of uniform stress in peri-implant bone without concentrations in a specific surface area of the implant [24,25,27,28,36]. These FEA findings are close to results of *in vivo* studies. Also, dependence on axial displacement of the force direction was found [37]. The axial force of 30 N generated much higher displacement than lateral. Therefore, the damping behaviour is more expected under the axial load transmission.

The non-axial loading of the implant increased the stress concentrations in peri-implant bone because of bending [20,21,23,26,38]. It is important to understand, that the axis of rotation locates at the top of the bone [36,39]. In FEA models under load of 100 N without any changes of other conditions except of loading direction (axial vs. oblique), the stress increased and its trend of concentration was revealed under oblique loading [20,21,23]. The stress increased specifically around the neck of the implant on cortical bone. Angled abutments created the same effect because they shifted the load from the implant axis [23,38]. Without changes of load direction following the increased abutment angulation from 0 to 15°, stress concentrations increased in cortical peri-implant bone. Consequently, the oblique load creates a bending effect, which affects the bone, especially around the rotation area but the different mechanical properties of bone layers determine different displacement of the implant body.

Other parameters of restorations such as cantilevers and C/I ratio could increase bending of the implant and stress or strain in the bone. Retrospective study shows the relation between bone loss and cantilevers [40]. The behaviour of different sized restorations was compared: single-unit, fixed partial, fixed full. Another retrospective study did not find significant bone loss around implant when distal cantilevers were constructed with full arch prosthesis [41]. So the number of implants could create a counterpoise and reduce the bending effect of cantilevers. The similar bending effect could be caused by the extended width of the implant crown. However, the study did not find an influence between the width of the crown and peri-implant bone loss [42]. Related FEA studies were not found.

Sotto-Maior et al. [34] performed an FEA study, in which the influence of different C/I ratio to stress distribution was investigated. 22.47% of cortical bone stress depended on C/I ratio. The stress increased with an increase of C/I ratio. When C/I = 2.5 stress concentrations increased more than twice [34]. The dependence between peri-implant bone loss and C/I ratio was confirmed in prospective clinical studies [43,44]. Otherwise, C/I ratio depends not only on crown length, but also on implant length. This supports the FEA study with the conclusion that short implants create higher stress at peri-implant cortical bone [45].

The shape of the implant could affect the stress distribution around the implant surface. According to FEA results, as the diameter of the implant decreased, the stress concentration increased [26,31,45]. Also, stress distribution depends on surface design [46,47] and thread configuration [32].

Abutment connection design also affects the stress concentration in peri-implant bone. The connection area could provide a stress-damping effect [48,49]. All studies comparing the effectiveness of conventional (non-platform switch) and platform switch abutments revealed that platform switch type abutments decreased stress concentrations in peri-implant bone [20-22,33] and its positive effect was higher for cortical bone than trabecular [23]. On the other hand, platform switch reduced stress from the bone, but accelerated on the interface of connection surfaces [21] and that could provoke strain for mechanical parts such as implant, screw and abutment. But we can conclude, that platform switch tends to be a damping element.

The concept of passive fit implies that there was no gap or strain induced by misfit of the framework prior to functional loading [50]. Misfits of prosthetic elements could generate peri-implant stress [18]. This FEA investigated peri-implant stress when theoretical misfit was recorded on implant-abutment level and on abutment-crown level. The stress was dependent on misfit. Aguirrebeitia et al. [19] approved similar findings in their study, where misfit of abutment was generated with changing of conical angle of abutment. They detected that discrepancy between contacting surface increased the stress in surrounding bone. The passive fit of implant and related prosthetic components were considered to be very important and its absence was thought to cause complications in biological tissues and mechanical failures [51]. Consequently, imperfections at the connection regions could generate overloading of peri-implant bone as well as in prosthetic parts [18,19,52]. It may be worth considering, that analog abutments or bases could cause the similar stress because of unmanaged imperfections.

The influence of restorative materials on stress distribution was not confirmed by FEA [26,34]. However, these results could be due to limitation of finite element models. The loading condition is mostly described as static with linear deformability. Materials with different elastic modulus were perfectly bonded without any displacement freedom [35]. Magne et al. in their *in vitro* study [53] detected that shock-absorbing capacity of implant restorations depends on damping behaviour of different dental materials under the cyclic loading conditions. The usage of composite materials damping behaviour was growing due to visco-elasticity of such material [54,55]. Changes could exist in restorative layers but that could not be detected by static linear FEA. If the damping effect of platform switch was detected, elastic prosthetic parts could accelerate the same phenomenon.

Magne et al. [53] described damping behaviour of periodontal ligament and its shock-absorbance. In clinical cases, when an implant restoration had a natural opposite tooth, the periodontal ligament of antagonistic could absorb significant part of the loading energy [56,57]. Authors established 0.2 mm peri-implant bone loss in cases with natural antagonist and 0.6 mm bone loss in cases with opposite implant restoration at the same time [56], and concluded, that higher bone level is in cases with opposite natural tooth [56,57].

Occlusal overloading was said to be the primary cause of biomechanical implant complications [58]. Implant loss because of direct overloading reasons was described in *in vivo* [59] study with rats and in retrospective study [60]. *In vivo* based older studies detected that in case of bacterial peri-implant inflammation and overloading could accelerate bone loss [61]. However, we have to agree with Pellegrini et al. [62] review, which stated that the detrimental effect of occlusal overload on bone-implant interface is still a controversial issue. The histological findings found in animal studies might not be straight usable in humans.

CONCLUSIONS

Peri-implant strain could be generated by non-axial loading, cantilever prosthetic elements, crown/implant ratio, type of implant-abutment connection, misfits, properties of restoration materials and antagonistic tooth. Finite element analysis studies are not erroneous methodically and the results correlate with other experimental and clinical findings. Due to the heterogeneity of finite element analysis studies and expression of their results, it is impossible to perform meta-analysis or systematic reviews.

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The authors report no conflicts of interest related to this study.

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