QUERIES - jop130633q

[AQ1] Please review the author byline and running heads to ensure that all author surnames are spelled correctly and that the author order is as meant.

[AQ2] This article and the abstract have been edited for clarity and flow throughout with the intent to retain original meaning. This includes text body and headings, all footnotes (affiliation and otherwise), any figures and their legends, and any tables and their legends, and any acronyms that have been spelled out per journal style. Please read carefully for completeness and definition, and confirm or amend as needed.

[AQ3] In Key words: Only those terms and phrases that match MeSH key words are allowed. Thus, some terms have been adjusted or deleted. Please provide additional MeSH terms (**total of 6 in all**) as needed (see http://www.nlm.nih.gov/mesh/MBrowser.html for common MeSH terms and phrases).

[AQ4] The manufacturer footnote symbols have been adjusted according to journal style. Please review the changes carefully.

[AQ5] Please confirm that supplementary Figs. 1 to 4 have been provided for online publication.

[AQ6] In paragraph 6 under Discussion, "fibrous connective tissue" correct as expansion of "fibro-CT"? Note that CT was used as an abbreviation for computed tomography elsewhere in the article.

[AQ7] Salutations are used in the Correspondence footnote. OK to add Dr.?

[AQ8] Please note that *P* values have been rounded to three significant digits when <0.01 and to two significant digits when >0.01 unless rounding would affect significance, according to AMA guidelines.

[AQ9] In the manufacturers footnote: What is meant for "SIN SW SIN"?

[AQ1] # Biomechanical Evaluation of Platform Switching: Different Mismatch Sizes, Connection Types, and Implant Protocols

Roberto S. Pessoa,*† Fábio J.B. Bezerra,‡ Ravel M. Sousa,* Jos Vander Sloten,† Marcio Zaffalon Casati,‡ and Siegfried V.N. Jaecques†§

[AQ2] **Background:** It is not yet well understood to what extent different implant–abutment mismatch sizes and implant–abutment connection types may influence the peri-implant biomechanical environment of implants in different clinical situations.

Methods: Computed tomography–based finite element models comprising a maxillary central incisor socket and 4.5 × 13 mm outer-diameter implants with external and internal hex connection types were constructed. The abutments were designed with diameters of 3.5 mm (platform switching [PS] with 1 mm of diametral mismatch [PS – 1]), 4.0 mm (PS with 0.5 mm of diametral mismatch [PS – 0.5]), and 4.5 mm (conventional matching implant–abutment design [CD]). Analysis of variance at the 95% confidence interval was used to evaluate peak equivalent strain (EQV strain) in the bone, bone volume affected by a strain >4,000 με (EQV strain >4,000 με), the peak von Mises stress (EQV stress) in abutment screw, and the bone–implant relative displacement.

Results: Similar bone strain levels (EQV strain and EQV strain >4,000 με) were encountered in PS – 1, PS – 0.5, and CD models for immediately placed implants, independent of the connection type. For immediately loaded implants, slightly smaller peak EQV strain and EQV strain >4,000 με were found for PS – 1. However, for both connection types in osseointegrated models, the higher the mismatch size, the lesser the amount of strain found.

Conclusions: The increase in mismatch size of PS configuration results in a significant decrease of strain levels in bone for osseointegrated implants, principally for external hex connections. No significant effect of PS could be noted in immediately placed implants. *J Periodontol 2014;85:*■■■-■■■.

KEY WORDS

[AQ3] **Dental implants; finite element analysis; tensile strength.**

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Peri-implant crestal bone remodeling has received increasing attention because higher emphasis is being placed on the esthetic results of implant therapy.[1] The position of the soft tissue margin at the facial and proximal aspects of the implant-supported crown directly depends on the bone-supporting level.[2,3] Therefore, peri-implant bone loss may negatively influence the soft tissue topography, leading to recession or absence of papillae.[2,3] In addition, the initial breakdown of the implant–tissue interface, which may lead to the failure of successfully osseointegrated implants, generally begins at the crestal region.[4,5] In this way, cervical peri-implant bone loss can jeopardize both the functional and esthetic outcomes of implant treatment.

Several hypotheses for these observed changes in crestal bone height have been suggested. Some authors concluded that a minimum width of peri-implant mucosa is required to establish a proper epithelial–connective tissue attachment.[6,7] If this dimensional criterion is not satisfied, crestal bone resorption will occur to ensure the establishment of such biologic width.[6] Other studies emphasized the potential role of the implant–abutment microgap of two-stage implants.[8-10] The butt–joint connection microgaps are associated with bacterial contamination that causes the

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formation of peri-implant chronic inflammatory infiltrate, thereby leading to bone resorption.[8-10]

Conversely, Lazzara and Porter[11] found a better long-term preservation of marginal bone around wide-diameter (5.0-mm) dental implants connected with standard-diameter (4.1-mm) restorative components. It has been advocated that this prosthetic concept, introduced in the clinical practice as "platform switching" (PS), may overcome some of the problems associated with two-piece implants.[11,12] The horizontally inward repositioning of the implant–abutment interface may expose more implant surface to which the connective tissue can attach, reducing marginal bone remodeling normally involved in biologic width formation. Moreover, it could move the implant–abutment microgap away from the crestal bone, shifting the inflammatory cell infiltrate inward, therefore reducing bone resorption.[11] These assumptions are supported by recent animal studies[13-15] and human histologic observations.[16,17] Furthermore, prospective-controlled studies,[18-24] literature reviews, and meta-analyses[25-27] confirmed that PS may preserve peri-implant bone height and soft tissue levels, although the magnitude of the observed marginal bone level alterations varied among the studies.

Additionally, some authors evidenced that the stress/strain concentrations caused by an excessive dynamic loading are capable of inducing the marginal bone loss around well-osseointegrated implants, even without the presence of an oral biofilm.[28] Duyck et al.,[28] in an experiment in rabbit tibiae, showed that the stress/strain concentration, caused by an excessive dynamic loading, is capable of inducing marginal bone loss around osseointegrated implants. Using finite element analysis (FEA) based on computed tomography (CT) images of tibiae samples, the authors estimated 4,000 $\mu\varepsilon$ as the strain value associated with overload-induced resorption.[28] In this way, it was also argued that the use of a narrow abutment in a PS configuration may shift the stress concentration away from the peri-implant marginal bone, thus decreasing its bone-resorptive effect.[29,30] Some authors concluded, by FEA, that the stress/strain levels in the cervical bone area at the implant was greatly reduced when the narrow-diameter abutment was simulated.[29,30]

However, in more recent FEAs, the biomechanical effectiveness of PS for reducing peri-implant bone stresses was questioned. Pessoa et al.[31] reported that a diametral horizontal mismatch of 0.5 mm (4.3-mm implant with a 3.8-mm abutment) did not add any important contribution to the biomechanical environment of the implants. Other authors also found that, although PS slightly reduces the stress/strain in crestal bone, it did not differ significantly between the models with and without PS.[32,33] These observations have been corroborated by a recent controlled clinical trial in which no statistically significant differences were found using implants with different diameters but the same implant/abutment mismatch.[20]

Nevertheless, PS has been a generic term used for different implant–abutment mismatch sizes and implant–abutment connection types among previous studies.[27] It is yet not well understood to what extent these parameters may influence the peri-implant biomechanical environment.[20] Furthermore, the biomechanical effect of these aspects on the stress/strain and displacement for PS in immediately placed and immediately loaded implants is a controversial issue and remains to be better investigated.[31] Therefore, the aim of this study is to evaluate the effect of different abutment mismatch sizes and implant–abutment connection types on the biomechanical environment of platform-switched implants in immediately placed, immediately loaded, and delayed loaded ("osseointegrated") clinical situations.

MATERIALS AND METHODS

An in-depth description of the methods applied to obtain the individualized finite element (FE) models used in the present study was reported and discussed previously.[31,34,35] Briefly, the CT scans of a maxillary central incisor extraction socket obtained from a dry maxilla were reconstructed in a three-dimensional solid model by thresholding using image-processing [AQ4] software.[‖]

The implants and prosthetic component computer-aided design solid models were obtained by reverse engineering to resemble the commercially available 4.5 × 13 mm outer-diameter implant,[¶] with external hex (EH) and internal hex (IH) connection types. The abutments were designed with diameters of 3.5 mm (PS with 1 mm of diametral mismatch [PS – 1]), 4.0 mm (PS with 0.5 mm of diametral mismatch [PS – 0.5]), and 4.5 mm (conventional matching implant–abutment design [CD]) (see sup- [AQ5] plementary Fig. 1 in online *Journal of Periodontology*).

The implants were imported in the same image-processing software of the bone model and positioned 1 mm deep inside the extraction socket, in a central position and a palatal direction.[36] The abutments and abutment screw models were subsequently aligned to the implants following the instructions from the implant manufacturer. All the abutments were 10 mm in height from the implant shoulder. The implant insertion hole in the extraction socket solid model was obtained by Boolean subtraction between the bone and implant solids.

‖ Mimics v.12.0, Materialise, Leuven, Belgium.
¶ SIN SW SIN, Sistema de Implantes, São Paulo, Brazil. [AQ9]

Bone, implant, abutments, and abutment screw models were meshed separately.[#] No simplifications were made regarding the macro-geometry of the implant system (i.e., truly spiral threads), in neither the implant–abutment connection nor the implant body. In addition, the bone mesh was tested for convergence.[36] The smallest elements in the constructed tetrahedral meshes were ≈50 µm in size. Different levels of mesh refinement were used for feature recognizing (e.g., at the threads).

The gray values of the CT images were used to assign the material properties of the elements contained in cortical and trabecular bone.[37] The values of the Young's modulus and Poisson ratio for the materials used in the present study were retrieved from the literature.[36]

Frictional contact elements were used to simulate the bone–implant interface in both immediately placed and immediately loaded implant models (frictional coefficient $\mu = 0.3$),[38] as well as the implant system component interfaces in contact ($\mu = 0.5$).[39] In addition, the socket healing was simulated in the immediately loaded and delayed loaded models by modeling a hard-tissue bridge at the alveolar ridge region. For the delayed loaded models (i.e., loading applied after implant osseointegration), the bone–implant interface was assumed as glued.

In the three loading magnitude situations, forces of 50 N (underloading), 100 N (normal loading), and 200 N (overloading)[40] were applied with 45 degrees of inclination in relation to the socket long axis in a palato-buccal direction on the top of the abutment central region. Models were fully constrained in all directions at the nodes on the mesial and distal borders.

The FE model analysis and postprocessing were accomplished by means of an FEA solver.[**] The results from the 54 models for the peak equivalent strain (EQV strain) in the bone, bone volume affected by a strain >4,000 µε (EQV strain >4,000 µε), the peak von Mises stress (EQV stress) in abutment screw, and the bone–implant relative displacement were interpreted by means of a general linear model and analysis of variance (ANOVA)[††] at a 95% confidence interval.[41] Abutment mismatch size, implant–abutment connection type, loading magnitude, and clinical situation (immediately placed, immediately loaded, and delayed loaded implants) were used as independent variables; EQV strain, EQV strain >4,000 µε, EQV stress, and bone–implant displacement were considered the dependent variables.

RESULTS

Table 1 shows the results for the peak EQV strain in the bone, EQV strain >4,000 µε, peak EQV stress in abutment screw, and bone–implant relative displacement for the three mismatch sizes (PS – 1, PS – 0.5, and CD), two connection types (EH and IH), three loading magnitudes (50, 100, and 200 N), and three clinical situations (immediately placed, immediately loaded, and osseointegrated). The results of the ANOVA on the relative contribution of each evaluated parameter (i.e., mismatch size, connection type, loading magnitude, and clinical situation) are shown in Tables 2 through 6.

Considering the same loading magnitude, similar bone strain levels (EQV strain and EQV strain >4,000 µε) were encountered in PS – 1, PS – 0.5, and CD models for immediately placed implants, independent of the connection type. For immediately loaded implants, slightly smaller peak EQV strain and EQV strain >4,000 µε were found for PS – 1. For this clinical situation, PS – 0.5 and CD presented comparable results. The highest differences in strain levels could be observed for delayed loaded (i.e., osseointegrated) implants. The higher the mismatch size, the lesser the amount of strain found in the osseointegrated model. The same pattern was followed independently of the connection type, although a slightly higher volume of bone affected by an EQV strain >4,000 µε could be seen for the IH connection, principally in 200-N loading. Supplementary Figure 2 in online *Journal of Periodontology* shows the strain magnitudes and distribution for the EH connection in all simulated clinical situations. All mismatch sizes presented a similar strain distribution for immediately placed implant simulations. For immediately loaded implants and osseointegrated situations, a smaller strain concentration can be seen for PS – 1. In these situations, only slight differences in strain magnitudes could be observed when comparing PS – 0.5 and CD (see supplementary Fig. 2 in online *Journal of Periodontology*).

Considering all independent variables together, loading magnitude (75.9%) and the clinical situation (10.6%) had the highest percentage contribution for the peak EQV strain in bone (Table 2). A rather small contribution could be found for abutment mismatch size (2.8%), although it was statistically significant (P<0.001). In Tables 3 and 4, the relative influence of mismatch size, connection type, and loading magnitude on the peak EQV strain and EQV strain >4,000 µε were evaluated for each different clinical situation separately. Because the differences between the mismatch size were subtle in the 50- to 200-N loading range, the results of 200-N loaded models were not included in this statistical analysis (Tables 3 and 4). For the peak EQV strain and EQV strain >4,000 µε, a negligible contribution of the mismatch size (0.1%)

MSC Patran v.2010r2, MSC Software, Gouda, The Netherlands.
** MSC.Marc and Mentat v.2010r3 software, MSC Software.
†† SAS/STAT v.9.1 statistical software, SAS Institute, Cary, NC.

Table 1.

Results for EQV Strain in Bone, Peak EQV Stress in Abutment Screw, and Bone–Implant Relative Displacement for all Simulated Models

Loading	Mismatch Size	Bone EQV Strains (με)		Screw EQV Stress (MPa)	Displacement (μm)
		Peak	>4,000 με		
EH					
Immediately placed					
50 N	PS – 1	4,015.8	0.06	179.7	4.9
	PS – 0.5	3,950.0	0.06	156.9	4.8
	CD	4,335.7	0.08	140.0	4.8
100 N	PS – 1	7,005.8	0.87	351.6	9.4
	PS – 0.5	6,989.7	0.87	307.0	9.6
	CD	6,879.7	0.85	267.8	9.5
200 N	PS – 1	18,222.0	4.5	614.0	19.1
	PS – 0.5	17,779.6	4.5	530.2	19.5
	CD	17,940.0	4.5	491.0	19.3
Immediately loaded					
50 N	PS – 1	3,253.2	—	184.8	1.7
	PS – 0.5	3,247.2	—	163.0	1.8
	CD	3,758.9	—	149.6	1.8
100 N	PS – 1	4,470.0	0.009	367.5	3.5
	PS – 0.5	5,117.5	0.06	325.7	3.8
	CD	5,778.2	0.07	289.5	3.8
200 N	PS – 1	8,783.8	1.3	539.4	7.4
	PS – 0.5	10,181.0	2.6	455.2	7.1
	CD	11,466.3	2.6	414.0	7.8
Osseointegrated					
50 N	PS – 1	1,792.2	—	187.7	—
	PS – 0.5	2,744.7	—	165.8	—
	CD	3,966.1	—	147.6	—
100 N	PS – 1	3,463.9	—	368.2	—
	PS – 0.5	3,700.0	—	325.4	—
	CD	5,098.8	0.02	285.0	—
200 N	PS – 1	6,709.8	0.21	528.0	—
	PS – 0.5	7,116.7	0.79	438.8	—
	CD	8,319.8	1.0	398.5	—
IH					
Immediately placed					
50 N	PS – 1	4,235.1	0.07	110.7	4.6
	PS – 0.5	4,502.9	0.09	110.9	4.7
	CD	4,485.9	0.07	112.7	4.6
100 N	PS – 1	6,598.6	0.7	199.3	9.4
	PS – 0.5	6,559.0	0.67	195.8	9.4
	CD	6,501.9	0.53	204.0	9.3
200 N	PS – 1	14,761.1	4.9	362.5	19.0
	PS – 0.5	14,058.7	5.1	358.1	18.9
	CD	13,795.3	4.9	367.3	18.7

and the connection type (1.5% and 0.5%, respectively) was observed for the immediately placed protocol (Tables 3 and 4). The higher influence of mismatch size (20.1% and 30.6%, respectively) and connection type (18.8% and 28.7%, respectively) was found for osseointegrated models. An intermediate contribution of both parameters was seen for EQV strain >4,000 με in immediately loaded implant simulations (Table 4).

With respect to the peak EQV stress in the abutment screw, PS – 1 presented the highest values independently of the connection type, clinical situation, and loading magnitude (Table 1; see supplementary Fig. 3 in the online *Journal of Periodontology*).

Table 1. (continued)

Results for EQV Strain in Bone, Peak EQV Stress in Abutment Screw, and Bone–Implant Relative Displacement for all Simulated Models

Loading	Mismatch Size	Bone EQV Strains (με)		Screw EQV Stress (MPa)	Displacement (μm)
		Peak	>4,000 με		
Immediately loaded					
50 N	PS – 1	3,417.1	—	75.9	1.0
	PS – 0.5	3,680.2	—	74.5	1.0
	CD	3,685.7	—	72.7	1.1
100 N	PS – 1	6,362.3	0.13	133.9	2.1
	PS – 0.5	6,722.8	0.2	122.5	2.2
	CD	6,844.5	0.29	126.5	2.2
200 N	PS – 1	11,646.9	3.1	233.6	4.4
	PS – 0.5	12,395.3	5.2	208.2	4.3
	CD	12,876.3	5.4	213.1	4.4
Osseointegrated					
50 N	PS – 1	2,203.8	—	73.9	—
	PS – 0.5	2,629.6	—	70.3	—
	CD	3,228.8	—	82.9	—
100 N	PS – 1	4,409.9	0.03	127.2	—
	PS – 0.5	5,162.4	0.07	119.3	—
	CD	6,479.7	0.11	121.3	—
200 N	PS – 1	8,428.6	2.3	221.9	—
	PS – 0.5	9,677.5	2.7	199.4	—
	CD	12,995.9	3.0	202.4	—

However, the screw EQV stress variation between the groups for the IH connection were minor (e.g., osseointegrated, 100 N: PS – 1 = 127.2 MPa; PS – 0.5 = 119.3 MPa; CD = 121.3 MPa) compared with the increase in screw EQV stress for PS in the EH connection (e.g., osseointegrated, 100 N: CD = 285.0 MPa; PS – 1 = 368.2 MPa). Comparing the connections, EQV stress in abutment screw for PS – 1 group was two-fold higher for EH (e.g., 368.2 MPa, osseointegrated, 100 N) than for IH (127.2 MPa, osseointegrated, 100 N) (see supplementary Fig. 4 in online *Journal of Periodontology*). In addition, an insignificant contribution of the mismatch size on screw EQV stress variations was found for the IH connection (0.6%) compared with EH (8.0%) (Table 5).

Regarding the bone–implant relative displacement in the immediate placement and immediately loaded simulations, the contribution of mismatch size was minor (0.04% and 0.01%, respectively) (Table 6). In addition, no differences were found in the displacement values between the PS – 1, PS – 0.5, and CD groups (Table 1).

DISCUSSION

The present FEA was performed to evaluate the effect of different mismatch size and connection type on the biomechanical environment of PS implants. It was demonstrated that both parameters have a significant contribution to the strains encountered in bone for osseointegrated implant simulations. In this clinical situation, the decrease of the strain in bone has a direct relationship with the increase of the mismatch size, regardless of the connection type. In addition, the stress in the abutment screw was also affected by the increase in mismatch size for the EH connection. Nevertheless, from a biomechanical point of view, the most important factors in implant survival, in immediately placed and immediately loaded protocols, are the control of functional loading and adequate intraosseous stability. No important effect of varying mismatch size or connection type could be noted in these situations.

For osseointegrated implants, the current FEA showed that, although the peak of EQV strain was slightly higher for PS – 0.5 and CD, respectively, compared with PS – 1, a minor bone volume affected by a strain >4,000 με was encountered for all mismatch sizes in a normal loading condition (50 to 100 N) at the region of a maxillary central incisor.[40] Similar observations were reported by Tabata et al.,[32] who evaluated the biomechanical behavior of a 5.0-mm-wide EH implant with a 4.1-mm abutment using FEA. The authors found a reduction of only 9.3% (30.2 to 33.3 MPa) in EQV stress for PS implants. Other authors also reported a stress/strain reduction of <10% for implants with PS compared with CD.[31,33] On the

Table 2.

[AQ8] **ANOVA for the Peak EQV Strain in the Bone**

Parameter	*df*	SS	MS	*P*	Contribution (%)
Mismatch size	2	25,245,352.1	12,622,676.1	<0.001*	2.8
Connection type	1	4,449,941.0	4,449,941.0	0.01*	0.5
Clinical situation	2	96,479,196.4	48,239,598.2	<0.001*	10.6
Loading magnitude	2	689,279,633.4	344,639,816.7	<0.001*	75.9
Abutment diameter × connection type	2	904,426.5	452,213.3	0.50	0.1
Clinical situation × loading magnitude	4	33,219,415.9	8,304,854.0	<0.001*	3.7
Abutment diameter × clinical situation	2	34,926,206.6	17,463,103.3	<0.001*	3.9
Connection type × clinical situation	4	15,732,924.9	3,933,231.2	0.001*	1.7
Abutment diameter × loading magnitude	4	7,053,620.2	1,763,405.1	0.04*	0.8
Connection type × loading magnitude	2	947,866.7	473,933.3	0.48	0.1

The different clinical situations were evaluated separately.
df = degrees of freedom; SS = sum of squares; MS = mean square.
* P <0.05; statistically significant.

Table 3.

ANOVA for the Peak EQV Strain in the Bone for 50- to 100-N Loading

Parameter	*df*	SS	MS	*P*	Contribution (%)
Immediately placed					
Mismatch size	2	77,431.07	38,715.53	0.84	0.1
Connection type	1	1,472,865.41	1,472,865.41	0.02*	1.5
Loading magnitude	1	87,474,556.08	87,474,556.08	<0.001*	91.0
Immediately loaded					
Mismatch size	2	4,204,266.95	2,102,133.48	0.03*	5.9
Connection type	1	189,907.11	189,907.11	0.56	0.3
Loading magnitude	1	66,579,888.12	66,579,888.12	<0.001*	92.8
Osseointegrated					
Mismatch size	2	13,064,526.11	6,532,263.06	<0.001*	20.1
Connection type	1	12,279,429.32	12,279,429.32	<0.001*	18.8
Loading magnitude	1	36,494,506.61	36,494,506.61	<0.001*	56.1

The different clinical situations were evaluated separately.
df = degrees of freedom; SS = sum of squares; MS = mean square.
* P <0.05; statistically significant.

contrary, Maeda et al.,[29] using FEA to compare a 4.0-mm implant restored with a matching abutment (CD) and with a 3.2-mm abutment (PS), concluded that the strain energy density in the cervical bone area at the implant surroundings was greatly reduced (from 34×10^{-6} kg for CD to 16×10^{-6} kg for PS) when the narrow-diameter abutment was simulated. Similar conclusions were presented by Chang et al.,[30] who evaluated the implant–bone interface stresses around PS (4.1-mm implant restored with a 3.4-mm abutment) and matching implants using three-dimensional FEA. The authors indicated that the maximum EQV stress in compact bone was lower in the PS model (84.3 MPa) than in the CD model (89.2 MPa), although this reduction was <10%.

It is important to emphasize that creating an accurate analytic model of a dental implant involves modeling of all possible aspects that may exert an influence within the region to be investigated. In producing realistic and reliable solutions for PS models, the modeling of the whole implant connection is desirable (i.e., connection design, abutment

Table 4.

ANOVA for the Bone Volume Affected by an EQV Strain >4,000 $\mu\epsilon$ for 50- to 100-N Loading

Parameter	*df*	SS	MS	*P*	Contribution (%)
Immediately placed					
Mismatch size	2	0.00631667	0.00315833	0.60	0.1
Connection type	1	0.02722500	0.02722500	0.04*	0.5
Loading magnitude	1	5.72006944	5.72006944	<0.001*	99.0
Immediately loaded					
Mismatch size	2	0.01342482	0.00671241	0.07	11.7
Connection type	1	0.02871104	0.02871104	0.002*	25.0
Loading magnitude	1	0.06445336	0.06445336	<0.001*	56.0
Osseointegrated					
Mismatch size	2	0.01327617	0.00663808	0.04*	30.6
Connection type	1	0.01243225	0.01243225	0.02*	28.7
Loading magnitude	1	0.01729225	0.01729225	0.005*	39.9

The different clinical situations were evaluated separately.
df = degrees of freedom; SS = sum of squares; MS = mean square.
* P <0.05; statistically significant.

Table 5.

ANOVA for the Peak EQV Stress in Abutment Screw

Parameter	*df*	SS	MS	*P*	Contribution (%)
EH					
Mismatch size	2	100,499.438	50,249.719	<0.001*	8.0
Clinical situation	2	995.267	497.633	0.56	0.1
Loading magnitude	2	1,143,448.048	571,724.024	<0.001*	91.3
IH					
Mismatch size	2	2,853.0410	1,426.5205	0.09	0.6
Clinical situation	2	114,286.7595	57,143.3798	<0.001*	22.3
Loading magnitude	2	391,699.2640	195,849.6320	<0.001*	76.7

The connection types were evaluated separately.
df = degrees of freedom; SS = sum of squares; MS = mean square.
* P <0.05; statistically significant.

design, internal implant thread design, and abutment screw design). Modeling assumptions and software limitations might lead to a number of inaccuracies within the obtained results.[34] The results reported in some studies on PS were obtained by quite simplified models that did not consider the internal geometry of the implant–abutment connection in detail.[29,30,32] This geometry is recognized as a key factor associated with the pattern and magnitude of stresses.[34,36,39] In addition, the frictional non-linear contact relationship between the implant–abutment components was ignored in previous models.[29,30,32] Contact and friction play essential roles in the mechanical behavior of the implant–abutment complex and are especially necessary in the simulation of butt–joint connection designs.[39] This configuration allows minor displacements between all components of the model without interpenetration. Under these conditions, the contact zones transfer pressure and tangential forces (i.e., friction) but not tension. Conversely, in bonded interfaces, the force is dissipated evenly in both the compressive site and the tension site.[34] Some FEAs showed remarkable differences in the values and even in the distribution of stresses between "fixed-bond" and "non-linear contact" interface conditions.[34,39] Moreover, even generic FE models, which intend to focus only on the relative influence of an implant parameter rather than on the absolute in vivo results, may be evaluated with respect to their coherence with available biologic data.[42] Hence, it is possible to determine whether numerical models are consistent in their predictive capacity and whether the provided information could be extrapolated, or at least be useful, to the clinical

Table 6.

ANOVA for the Bone–Implant Relative Displacement

Parameter	*df*	SS	MS	*P*	Contribution (%)
Immediately placed					
Mismatch size	2	1.050370	0.525185	0.69	0.04
Connection type	1	6.134074	6.134074	0.04*	0.2
Loading magnitude	2	2,832.833704	1,416.416852	<0.001*	94.7
Immediately loaded					
Mismatch size	2	0.0292593	0.0146296	0.95	0.01
Connection type	1	37.1674074	37.1674074	<0.001*	14.9
Loading magnitude	2	208.6114815	104.3057407	<0.001*	83.9

The different clinical situations were evaluated separately.
df = degrees of freedom; SS = sum of squares; MS = mean square.
* $P < 0.05$; statistically significant.

context. Some criteria for adaptive bone modeling (bone gain and bone loss) were proposed in the relevant biomechanical literature and might be used as reference for FEA results.[28,34,35,43,44] Under this context, and not taking into account the simplifications in the models, all the results assessed for both the PS and CD in previous FEAs are still within the limit of cortical bone tolerance.[29-33] However, in a possible overloading condition (200 N) for osseointegrated implants, the current FEA showed some advantage for the PS when principally comparing the strain levels in the PS – 1 and CD groups, independently of the connection type. For instance, the EH connection presented a significantly higher volume of bone affected by a strain >4,000 με for CD (1.0 mm^3) compared with PS – 1 (0.21 mm^3). Otherwise, the difference between CD (1.0 mm^3) and PS – 0.5 (0.79 mm^3) was significantly smaller. These results corroborate a previous FEA from Pessoa et al.[31] The authors did not find a biomechanical advantage for a PS with a diametral horizontal mismatch of 0.5 mm. They argued that a larger abutment results in a greater area for loading dissipation on the implant platform and thus in a smaller stress concentration in the implant–abutment interface. Conversely, although a higher stress concentration might be seen in the reduced abutment diameter in PS implants, a greater distance should be covered by the stress on the implant shoulder prior to it reaching the marginal bone. For certain mismatch sizes, a similar strain magnitude will be found in the peri-implant bone.[31] Accordingly, Canullo et al.[20] found no statistically significant differences in marginal bone loss using implants with different diameters but the same implant/abutment mismatch (0.5-mm diametral horizontal mismatch), concluding that biologic and microbiologic factors were prevalent compared with biomechanical factors in the formation of peri-implant bone remodeling for that amount of mismatch. However, even from a biomechanical point of view, there might be a minimal mismatch size from which the PS becomes more efficient. This assumption is in agreement with a controlled clinical trial from Canullo et al.[18] that demonstrated that marginal bone levels were even better maintained with increasing implant/abutment mismatch.

Comparing the strain parameters for the different connection types, a higher EQV strain and EQV strain >4,000 με were seen for EH regardless of the mismatch size. Pérez del Palomar et al.,[45] when comparing rigid and resilient implant–abutment connections, also found greater stress values in the bone for the rigid ones. The resilient component in the connection was shown to absorb some of the load, which resulted in a smaller stress in the bone for this kind of implant. Yang and Maeda[46] reported the same observation in an experimental strain-gauge study. The authors discussed that the decreasing strain values for PS implants were more pronounced in EH than in IH, which indicates that the effect of PS might be more obvious in the EH connection.[46]

Conversely, the present FEA verified a significantly higher EQV stress in abutment screw for the EH compared with the IH connection. Moreover, a remarkable increase in EQV stress for the EH abutment screw was observed when comparing CD with PS – 0.5 and PS – 1, respectively. On the contrary, compared with EH, IH always maintained a lower stress concentration in abutment screw, even for PS configurations. In this respect, Merz et al.[39] demonstrated that, when loads are applied over the abutment in an EH configuration, there is no positive or geometric locking. In this way, under lateral or oblique loading, the abutment separates from the implant and tends to tilt about a small area on the implant shoulder, and thus the rising stress is absorbed mainly by the abutment screw.[34,36] Differently, in an IH connection, the lateral wall of the abutment protects the abutment screw from excessive stress.[36]

Concerning the immediately placed and immediately loaded implants, one of the most critical elements for the promotion of a safe biomechanical environment for an uneventful peri-implant bone tissue formation is a stiff bone–implant interface, allowing low implant micromovement in bone. Vandamme et al.[47] demonstrated that an implant displacement between 30 and 90 μm positively influenced osseointegration compared with no implant displacement. Conversely, micromovement beyond 150 μm [AQ6] can induce fibrous connective tissue formation, preventing immediately loaded implant osseointegration.[48] In this regard, all the evaluated models presented micromovements within the levels acceptable for implant osseointegration. In addition, the values of relative displacement were not influenced by either the mismatch size or the connection type. Also, Hsu et al.[33] evaluated PS in immediately loaded implants and reported no significant differences on implant micromotion and only a slightly higher strain levels for CD. Likewise, a small influence of PS on the bone strain magnitudes were found in the present study for immediately loaded implants.

Furthermore, in immediate placement simulations, the mismatch size and connection type did not influence bone strain parameters. Hansson[49] observed that, when the implant–abutment connection was positioned 2 mm coronally from the bone level, the effects of different connections were the same. In the present study, similar tendencies are observed in immediately placed implant simulations, probably because of the initial bone defect at the marginal region. This bone gap positioned the implant–abutment connection far from the bone, eliminating the possible influence of PS or connection types.[38]

Although it is an incontestably useful tool to obtain information that is difficult to acquire from laboratory experiments or clinical studies, the results obtained by FEA should be interpreted with some caution. The assumptions made during the process of developing an FE model, principally regarding the material properties and the interface conditions, limit the validity of the absolute values of the stress/strain and displacement calculated in a model in which an experimental validation was not accomplished. Otherwise, the association of the FEA with a statistical analysis was demonstrated as capable of accurately interpreting the relative influence that each of the input parameters have on the encountered results of implant FEAs.[31,34,36,41] Additionally, the modeling of bone-adaptive processes is not one of the aims of the current FEA. The precise determination of the loading level that separates mechanical loading into acceptable, osteogenic, or failure-inducing levels is difficult and until now unresolved. In addition, although some authors considered 4,000 με as a possible threshold for pathologic bone overload rather than only strain amplitude, loading frequency and number of loading cycles are parameters capable of greatly influencing the cortical bone adaptive response.[43] The loading applied in the presented simulation was static, and bone responds to dynamic rather than to static loads.[28]

CONCLUSIONS

Within the limitation of the present FEA, the following can be concluded: 1) The increase in mismatch size of the PS configuration results in a significant decrease of strain levels in bone for osseointegrated implants. 2) The effect of PS is more pronounced in EH connections. 3) No significant effect of PS could be noted in immediately placed implants, regardless of the connection type. 4) PS increases the stress in the abutment screw for an EH connection, whereas an IH connection can maintain lower stress levels in the abutment screw, regardless of the abutment mismatch size.

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