

# Evaluation of the Mechanical Reliability of Different Implant-Abutment Connections for Single Crowns According to the ISO 14801 Fatigue Test Protocol

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**Purpose:** The aim of this in vitro study was to evaluate the mechanical behavior regarding dynamic fatigue of different implant-abutment connections and the unitary indication of abutments for all regions of the mouth. **Materials and Methods:** This experimental study developed according to international standards (ISO 14801:2007) was performed using five types of implants and abutments: G1—external hex smart implant and 17-degree universal abutment (EHS); G2—cortical external hex implant and 17-degree universal abutment (EHTi); G3—internal hex implant and 30-degree universal abutment (IH); G4—Morse taper implant (11.5 degrees) and 17-degree universal abutment (MT11.5); and G5—Morse taper implant (16 degrees) and 30-degree universal abutment (MT16). A 15-Hz cyclic loading was applied to the specimens with the maximum number of cycles set at  $5 \times 10^6$ . Success was defined when three samples supported 5 million cycles without failure. The maximum load supported from each group after dynamic loading was recorded. The Spearman correlation and the Lowess method were used to analyze the correlation between the number of cycles and the applied load, and the Kruskal-Wallis and Nemenyi tests were used for comparison between the abutments when reaching 5 million cycles. **Results:** There was a negative correlation ( $r < 0.00$ ) and significant difference ( $P < .05$ ) between the number of cycles and the load for each type of implant and abutment. The load values supported by each group after cyclic loading to achieve 5 million cycles were as follows: EHS, 225 N; EHTi, 215 N; IH, 220 N; MT11.5, 210 N; and MT16, 240 N. The MT16 implant-abutment assembly presented a significantly higher load ( $P = .024$ ) than the MT11.5 implant-abutment assembly. **Conclusion:** All implant-abutment connections investigated in this study resisted average occlusal force values reported as acceptable in the literature and may be indicated for any region of the mouth. *Int J Oral Maxillofac Implants* 2021;36:47–54. doi: 10.11607/jomi.7965

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The use of osseointegrated dental implants has become a successful procedure for the treatment of complete or partial edentulism and single-tooth replacements in both the anterior and posterior regions of the mouth. Implant-supported rehabilitations are

subject to substantial masticatory cyclic loadings during function; consequently, mechanical complications of the implant/prosthetic system, such as fracture or loosening of the abutment screw or fracture of the implant, may occur.<sup>1–3</sup>

The dental literature provides various testing protocols for the evaluation of dental implant mechanical reliability,<sup>4</sup> but in most of the available scientific studies, testing is performed by applying only part of the procedures provided by international standards (ISO 14801).<sup>5,6</sup> The mechanical tests of dental implant systems, when carefully following the ISO 14801 standard, provide a powerful and accurate tool for mechanical reliability evaluation in accordance with globally recognized data that may allow identifying indications and limitations of their use.<sup>5,6</sup> In vitro approaches are more appropriate as initial steps, before the application of any in vivo method.<sup>7,8</sup> Fatigue tests lead to determination of the fatigue limit of the dental implant, conventionally defined as the maximum value under which

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a system has a useful life determined by a number of cycles.<sup>9,10</sup> The fatigue limit is greater than the stress that the teeth support during the normal chewing process and confirms the appropriate structural design of the used device.<sup>9,10</sup>

Tapered connections showed superiority over non-tapered (internal and external) in terms of sealing, microgap formation, torque maintenance, and abutment stability. In vivo studies (animals and humans) have shown that tapered systems have less marginal bone loss around implants in most cases compared with nontapered systems.<sup>11</sup> When a finite element analysis method was used to evaluate the internal tapered connections and external connections, it was observed that the internal tapered connections presented better mechanical characteristics compared with the external connections.<sup>12</sup> In addition, the internal tapered interface presents statistically less bone loss after 12 months of placement compared with an external hexagonal connection in implants placed at the bone level.<sup>13</sup> The tapered interface, the opposite of external hexagon, results in a relatively tight junction due to friction between the implant and abutment.<sup>14</sup> Steinebrunner et al (2008) evaluated six different implant systems in vitro: four were internal screw-retained connections, and two were external connections. It was found that different implant-abutment connection designs exhibited significant differences in survival time under dynamic loading and in maximum fracture strength. Internal connections showed better properties with respect to fatigue and fracture resistance compared with other implant systems with external connections.<sup>15</sup>

The main challenge in the development of implant-abutment connection designs relies on reducing/eliminating the incidence of mechanical failures and improving the soft tissue and prosthetic interface.<sup>2,13,16</sup> Thus, evaluation of the fatigue strength that supports different internal and external connections can provide information about the system mechanical behavior when used as unitary crowns.<sup>16</sup> The implant-abutment connection design can present a significant influence on the carrying capacity, and the failure occurring due to overload differs between the connections.<sup>17</sup> All tested implant-abutment connection designs must withstand clinically relevant forces. Therefore, it is important to perform static and dynamic loading tests.<sup>17,18</sup>

Marchetti et al (2016) evaluated the mechanical performance under fatigue stress using implants of 3.80 mm in diameter and 12 mm in length (BioHorizons). Implant samples that were subjected to a  $5 \times 10^6$  cyclic loading with a maximum load of 172 N (40% rupture load) were reported to survive, while the samples subjected to the higher loads failed between 8,452 and 13,526 cycles. In only one sample, with a maximum load of 215 N (50% of the rupture load),  $5 \times 10^6$  cycles were completed.<sup>6</sup>

Marchetti et al (2014) reported that at a load level of 60% of the rupture load (300 N), one of the two samples failed after 27,732 cycles, while the other was partially damaged. Samples subjected to higher values (400 N, corresponding to 80% of the mean rupture load) failed between 12,678 and 15,387 cycles.<sup>5</sup>

The purpose of this in vitro study was to evaluate the mechanical behavior regarding dynamic fatigue of different implant-abutment connections and the indication of different abutments for all regions of the mouth, considering unitary crowns.

## MATERIALS AND METHODS

### Sample Preparation

Four types of implant connections (Neodent) were investigated in this study and divided into five groups. Each group consisted of a commercially available implant system with a two-piece prosthetic abutment:

- G1: HE Smart Titamax Cortical Implant Ø (3.3) 3.3/13 mm and angled universal abutment 17 degrees Ø 3.3/4 mm (EHS)
- G2: Titamax Ti Cortical Implant Ø (3.3) 3.3/13 mm and angled universal abutment 17 degrees Ø 3.3/4 mm (EHTi)
- G3: II Plus Titamax Cortical Implant Ø (4.3) 3.75/13 mm and II Plus angled universal abutment 30 degrees Ø 4 mm (IH)
- G4: CM Titamax Cortical Implant, Ø 3.5/13 mm with 11.5-degree taper angle and CM angled universal abutment exact 17-degrees Ø 3.3/6/3.5 mm (MT11.5)
- G5: GM Titamax Cortical Implant Ø 3.5/13 mm with 16-degree taper angle and GM angled universal abutment exact 30 degrees Ø 3.3/6/3.5 mm (MT16; Table 1)

Implants were placed in polyacetal bases (Ø 15/20 mm; PolyBrasil), with modulus elasticity of 3 GPa. The implants were maintained with 3-mm exposure. The abutments were placed on the implants using three different tightening forces: 32 Ncm (EHS and EHTi), 20 Ncm (IH and MT16), and 15 Ncm (MT11.5; Table 1). A digital prosthetic ratchet (TQ-680, Instrutherm) was used for tightening the prosthetic abutments to the implants (Fig 1).

### Mechanical Tests

Prior to the dynamic fatigue, a static load test was performed on the Universal Test Machine (ElectroPuls 3382, Instron) to provide an initial load for the dynamic test. The applied load followed the direction of angulation established in ISO 14801:2007.

**Table 1** Test Groups and Conditions

Groups	Manufacturer	Implant	Abutment	Abutment torque (Ncm)	Connection type/index
EHS	Neodent	Titamax HE Smart Cortical Ø (3.3) 3.3/13 mm	Universal Angled Abutment 17 degrees Ø 3.3 x 4 mm	32	External hexagon/dodecagon
HTi	Neodent	Titamax Ti Cortical Ø (3.3) 3.3/13 mm	Universal Angled Abutment 17 degrees Ø 3.3 x 4 mm	32	External hexagon/hexagon
IH	Neodent	Titamax II Plus Cortical Ø (4.3) 3.75/13 mm	Universal Angled Abutment II Plus 30 degrees Ø 4 mm	20	Internal hexagon/internal hexagon
MT11.5	Neodent	Titamax Cortical CM Ø 3.5/13 mm	Universal Angled Abutment CM exact 17 degrees Ø 3.3/6/3.5 mm	15	Morse taper/internal hexagon
MT16	Neodent	Titamax GM Acqua Ø 3.5/13 mm	Universal Angled Abutment GM exact 30 degrees Ø 3.3/6/3.5 mm	20	Morse taper/internal hexagon



**Fig 1** Digital prosthetic ratchet (TQ-680, Instrutherm) used to tighten the prosthetic abutments to the implants.



**Fig 2** Static and dynamic loading: The hemispherical device is positioned on the abutment for application of vertical cyclic loads following ISO 14801:2007.

Initially, static loading was performed using the same configuration as the dynamic loading test. The maximum load supported by three samples was used to perform the dynamic test (speed of 1.0 mm/min). For the dynamic test, initial loads were defined as 60% of the maximum static loads found in the static test.

A dynamic test machine (ElectroPuls E1000, Instron) was used to perform the mechanical fatigue test, with a sample number of nine specimens or higher for each group according to ISO 14801:2007, which establishes that at least four different loads should be tested, in which three specimens should withstand  $5 \times 10^6$  cycles without failure. A hemispheric shaped device made of cobalt-chromium alloy (Coronel, Etkon) was positioned on the abutments. Aiming to simulate a worst-case condition, the samples were positioned in a stainless-steel template, and angled loading (in relation to the implant axis) was applied according to the abutment angulation. For abutments with 17 degrees, the load had 27 degrees of angulation, and for abutments with 30 degrees, the load had 40 degrees of angulation (Fig 2). Sinusoidal loading oscillated between a maximum value

(60% of breaking load) and a minimum value (10% of the maximum value). The frequency used in the test was 15 Hz. The bending moment was measured considering the lever arm of the system and the maximum force applied. The mathematical formula follows:

$$M = y \text{ (Lever arm)} \times F \text{ (Force)}$$

When the previous sample survived  $5 \times 10^6$  cycles, the next sample ran on the increased previous load by a predetermined amount. If the previous sample failed, the next sample would run at the previous level minus the default value. All experiments were conducted under dry conditions at room temperature. Data analysis was performed by Spearman correlation between the number of cycles and the load. To illustrate this correlation for each type of abutment, dispersion diagrams were used with the smoothed curves adjustment by the Lowess method. The descriptive analysis of the bending moment was also described. The Kruskal-Wallis test was used to compare loads between the abutments when reaching

**Table 2 Bending Moment Calculated for EHS**

Sample	Reference load (%)	Maximum load (N)	Cycles	Failure
1	60	300	25,910	Implant thread near anchorage base
2	60	300	25,132	Implant thread near anchorage base
3	55	275	79,544	Implant thread near anchorage base
4	55	275	29,739	Implant thread near anchorage base
5	50	250	137,495	Implant thread near anchorage base
6	50	250	109,090	Implant thread near anchorage base
7	45	225	5,000,000	Without fail
8	45	225	5,000,000	Without fail
9	45	225	5,000,000	Without fail

**Table 3 Bending Moment Calculated for EHTi**

Sample	Reference load (%)	Maximum load (N)	Cycles	Failure
1	60	270	33,505	Implant thread near anchorage base
2	60	270	45,759	Implant thread near anchorage base
3	55.5	250	43,839	Implant thread near anchorage base
4	55.5	250	58,803	Implant thread near anchorage base
5	51.5	232	99,034	Implant thread near anchorage base
6	51.5	232	136,657	Implant thread near anchorage base
7	47.8	215	5,000,000	Without fail
8	47.8	215	5,000,000	Without fail
9	47.8	215	5,000,000	Without fail

**Table 4 Bending Moment Calculated for IH**

Sample	Reference load (%)	Maximum load (N)	Cycles	Failure
1	60	357	18,974	Implant thread near anchorage base
2	60	357	12,209	Implant thread near anchorage base
3	50	298	5,000,000	Without fail
4	50	298	230,500	Prosthetic abutment screw fractured
5	45	268	1,347,583	Implant thread near anchorage base
6	45	268	851,583	Implant thread near anchorage base
7	45	268	547,632	Prosthetic abutment screw fractured
8	40	238	4,805,751	Implant thread near anchorage base
9	40	238	5,000,000	Without fail
10	40	238	5,000,000	Without fail
11	40	238	499,799	Implant thread near anchorage base
12	40	238	5,000,000	Without fail
13	40	238	2,698,327	Prosthetic abutment screw fractured
14	37	220	5,000,000	Without fail
15	37	220	5,000,000	Without fail
16	37	220	5,000,000	Without fail

5 million cycles, and in the multiple comparison, the Nemenyi test was used. Analyses were performed using the R analysis software (version 3.5.1).

## RESULTS

The number of cycles means the number of times the sample has received the specific load. The values resisted by the samples after the static loading test were as follows: EHS, 500 N; EHTi, 450 N; IH, 595 N; MT11.5, 433 N; and MT16, 450 N. Loads initially applied to the dynamic loading test (60% maximum static load value) of the samples are shown in Tables 2 to 6 (EHS, 300 N; EHTi, 270 N; IH, 357 N; MT11.5, 260 N; and MT16, 270 N).

The samples were submitted to 5 million cycles of dynamic load. At least three samples from each group supported a given load. According to ISO 14801:2007, this value is the maximum supported in dynamic loading. The maximum values supported for each group in dynamic loading were as follows: EHS, 225 N; EHTi, 215 N; IH, 220 N; MT11.5, 210 N; MT16, 240 N (Tables 2 to 6). Regarding the number of cycles, IH abutments had the lowest minimum number of cycles per million (0.01), while MT11.5 and MT16 had the highest values (0.04; Table 7).

There was a negative ( $r < 0.00$ ) and significant ( $P < .05$ ) correlation between the number of cycles and the load for each type of implant, which means the higher the load, the lower the number of cycles. The implant-abutment assemblies of the EHS presented the lowest correlation between the load and the number of cycles (Table 8). In addition, the correlation between the number of cycles and the bending moment was equivalent to the number of cycles and the load.

Table 9 shows the mean and SD of the values for bending moment.

Titamax CM Cortical implant (MT11.5) had the lowest values for mean, minimum, and maximum. One can observe the loads that withstood (minimum) and the loads where there were failures (maximum) in Table 9. Figure 3 shows a box plot with the results presented in Table 9.

The values obtained for load versus the numbers of cycles were plotted, and the relations between the systems were evaluated. Figure 4 shows the dispersion diagram with nonparametric regression adjustment by the Lowess method for each type of implant.

Table 10 shows the comparison of loads by reaching the maximum number of cycles (5 million). It was observed that there was a significant difference ( $P = .007$ ) between at least one implant-abutment pair, and for the multiple comparisons test, the MT16 implant-abutment assembly presented a significantly higher load ( $P = .024$ ) than the MT11.5 implant-abutment assembly. It should be noted that, although the IH implant-abutment assembly required at least five different loads to reach a sufficient value, that load value in which the implant reached 5 million was 220 N, and did not show a significant difference from the other groups.

## DISCUSSION

The mechanical reliability of a dental implant system is a term used to identify indications and limitations for the use of a specific implant system.<sup>5</sup> The mechanical failure of an implant-prosthesis system may be related to excessive flexing of the screw joint against insufficient tightening force or intrinsic limits on the strength of the material. In addition, it may also be related to a “fit” and loosening effect of the components or to a design mismatch.<sup>19</sup> However, the

**Table 5** Bending Moment Calculated for MT11.5

Sample	Reference load (%)	Maximum load (N)	Cycles	Failure
1	60	260	25,910	Implant thread near anchorage base
2	60	260	25,132	Implant thread near anchorage base
3	55.5	240	79,544	Implant thread near anchorage base
4	55.5	240	29,739	Implant thread near anchorage base
5	52	225	137,495	Implant thread near anchorage base
6	52	225	109,090	Implant thread near anchorage base
7	48.5	210	5,000,000	Without fail
8	48.5	210	5,000,000	Without fail
9	48.5	210	5,000,000	Without fail

**Table 6** Bending Moment Calculated for MT16

Sample	Reference load (%)	Maximum load (N)	Cycles	Failure
1	60	270	41,651	Implant thread near anchorage base
2	60	270	37,980	Implant thread near anchorage base
3	57.8	260	45,248	Implant thread near anchorage base
4	57.8	260	44,308	Implant thread near anchorage base
5	55.5	250	113,253	Implant thread near anchorage base
6	55.5	250	88,807	Implant thread near anchorage base
7	53.5	240	5,000,000	Without fail
8	53.5	240	5,000,000	Without fail
9	53.5	240	5,000,000	Without fail

**Table 7** Descriptive Analysis of Maximum and Minimum Strength and Number of Cycles

Groups	Cycles	Cycles per million
EHS	5,000,000	0.03
EHTi	5,000,000	0.03
IH	5,000,000	0.01
MT11.5	5,000,000	0.04
MT16	5,000,000	0.04

**Table 8** Correlation Between Number of Cycles and Load for Each Type of Abutment

Groups	$r^a$	$P$
EHS	-0.72	.002
EHTi	-0.99	< .001
IH	-0.95	< .001
MT11.6	-0.99	< .001
MT16	-0.95	< .001

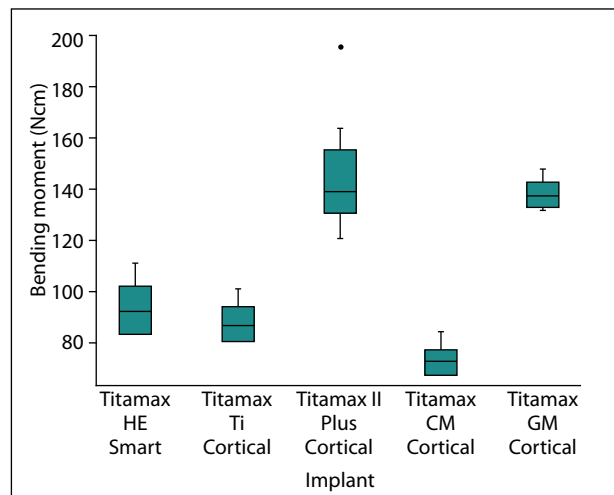
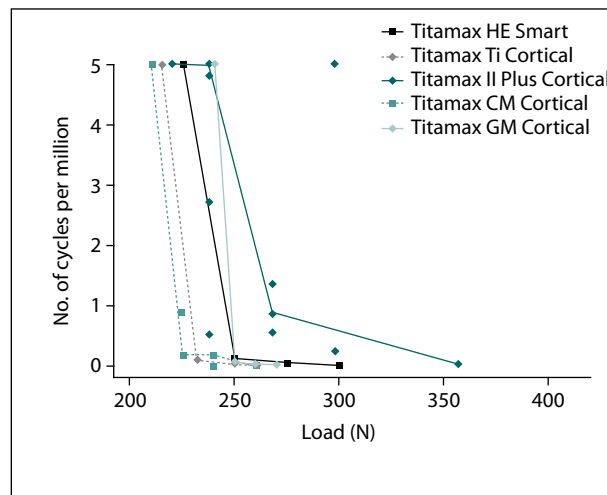
<sup>a</sup>Spearman correlation.

effect of a specific connection design on the mechanical strength of the screw joint in a dental implant remains uncertain, as demonstrated by the large number of commercially available configurations. For these reasons, the study of the mechanical properties of prosthetic implant systems is a critical research topic.

Specifically, the present study investigated the mechanical behavior of implant systems with the worst case for abutment design, assumed here as angled abutments that are indicated for all regions of the mouth after exposure to biomechanical stresses for 5 million load cycles. The results

**Table 9** Descriptive Analysis of Quantitative Variables

Groups	n	Bending moment (Ncm)						
		Mean	SD	Minimum	1st quartile	2nd quartile	3rd quartile	Maximum
EHS	9	95.61	11.31	83.3	83.3	92.5	101.8	111
HTi	9	89.31	8.36	80.4	80.4	86.8	93.5	101
IH	16	145.48	24.13	121	121	139.15	155.65	196.4
MT11.5	9	74.4	6.48	67.6	67.6	72.4	77.3	83.7
MT16	9	139.33	6.73	132	132	137.5	143	148.5

**Fig 3** Box plot of the bending moment by type of implant-abutment assembly.**Fig 4** Dispersion diagram between the number of cycles and the load for each type of implant-abutment assembly.**Table 10** Comparison of Loads Between Groups Reaching 5 Million Cycles

Groups	Load (N)	$P^a$	Multiple comparison ( $P$ ) <sup>b</sup>				
EHS	225		EHS	HTi	IH	MT11.5	MT16
HTi	215		.592	–	–	–	–
IH	220	.007	.951	.951	–	–	–
MT11.5	210		.178	.951	.592	–	–
MT16	240		.951	.178	.592	.024*	–

<sup>a</sup>Kruskal-Wallis test; <sup>b</sup>Nemenyi test.

\*Statistically significant.

show that the preparation of the implants as well as the repetitive load present a negative influence in the fracture loads of implants and prosthetic components.<sup>20</sup> The best way to generate data on fracture strength and implant longevity has been the fatigue tests.<sup>21</sup> In the present study, in addition to chewing simulation, the test conditions were carefully chosen to simulate an unfavorable clinical situation with reduced bone support. A distance of 3 mm between the implant shoulder and the crestal bone level was prepared to simulate a

representative case of bone loss.<sup>5,6</sup> The load was applied off-axis according to ISO 14801 and previous studies.<sup>5,6</sup> The present study showed that small component design changes are only needed to meet the mechanical requirements of each system, since behavior and mechanical capacity were acceptable and similar in terms of values (Table 2). The values obtained in the present research support the current standards of strength for dental implants and could suggest that the implants would support the clinical occlusal load for up to 20 years.<sup>20</sup> However, clinical studies presented in the literature showed that dental titanium implants are in place with good esthetic and functional activities for up to 35 years.<sup>22</sup>

Although the determination of maximum occlusal force is widely used in dentistry, whether in order to understand the masticatory mechanisms or in studies related to diseases, few studies address the maximum occlusal force of each tooth and its relation to the masticatory force.<sup>23,24</sup> The variation in occlusal forces may be related to age, sex, muscle size, degree of edentulism, bone shape, and parafunction.<sup>25</sup> The maximum occlusal forces in the posterior dentition were reported to range from 250 to 400 N and from 140 to 170 N in the

anterior dentition.<sup>23,24</sup> The normal or physiologic chewing forces for posterior dentition varied from 110 to 125 N and from 60 to 75 N in the anterior dentition<sup>23,24</sup> and should be considered, noting that clinically it is difficult for the patient to use a maximum occlusal force. In the present study, all implant-abutment groups supported loads above 210 N in dynamic loading, and the MT16 implant-abutment assemblies presented a significantly higher load ( $P = .024$ ) than the MT11.5 implant-abutment assemblies. Fortijn-Tekamp et al (2000) found that the relationship between masticatory strength and maximum occlusal force varies from 30% to 54% depending on the system considered, and this variability of the results happens due to the technique tested and also to the position of the teeth, which do not allow complete simulation of the actual chewing condition. Thus, to estimate the masticatory force, a ratio of 54% for the anterior region and 50% for the posterior region was applied on the results of maximum occlusal force.<sup>23</sup>

In another study, straight and angled abutments subjected to mechanical fatigue for  $2 \times 10^6$  cycles were compared, and angled abutments were more susceptible to clinical failures that are reported with screw problems and may require additional maintenance by the dentist.<sup>26</sup> Another study reported a higher percentage of angled abutment screw fractures compared with straight abutments.<sup>27</sup> However, the use of angled abutments is necessary in some cases of implants placed in the wrong position, and the present study, despite not having assessed preload, showed that angled abutments withstand high loads, following the ISO 14801 standard.

The indexed internal tapered interface connection was compared with an indexed hexagonal connection, and it was found that the internal tapered interface exhibited greater resistance to bending moments at the implant-abutment interface.<sup>28</sup> Another study reported the greater capacity to withstand loads of the internal tapered connections compared with external and internal hexagonal connections.<sup>29</sup> In the present study, the implant-abutment assemblies with internal tapered connection of MT16 presented the highest values of load compared with the internal and hexagonal connections of the other groups tested. The loading value increase in MT16 compared with MT11.5 can be explained by the increase in the implant-abutment contact area (MT11.5: 0.97 mm and MT16: 1.85 mm) and increase in the size of the index area (hexagon) of MT16 implants (MT11.5: 1.04 mm and MT16: 1.48 mm).

## CONCLUSIONS

Within the limitations of this in vitro study, it can be concluded that the implant-abutment systems

investigated have presented good mechanical reliability following the ISO 14801:2007 standard and constantly resisted the average values of occlusal force reported in the literature. The implant-abutment assemblies of Morse taper connection (MT16) supported the highest dynamic loads (240 N) after 5 million cycles. However, all implant-abutment assemblies presented sufficient values of strength (210 N) above normal values of occlusal mastication and may be indicated for all regions of the mouth.

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