Analecta Technica Szegedinensia
Vol. 17, No. 3 ISSN 2064-7964 2023

STATIC AND DYNAMIC COMPRESSION LOAD TESTS OF CONICALLY CONNECTED, SCREW FIXED DENTAL ABUTMENT – IMPLANT ASSEMBLIES

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Received: 25th April; Accepted: 05th June

ABSTRACT

The key for the long-term success of dental implants is the mechanical stability of the implant and the abutment anchored in it. The conical connection between screwed dental implants and abutments has good mechanical stability. However, with long-term use of the dental restoration fixed on a dental implant in the oral cavity, mechanical deformation of the assembled abutment in the implant and loosening of the fixing screw often occur, which affects long-term functionality. To study these processes, static compression loading tests were performed with various conical angle connections (35°, 55°, 75° and 90°) using Grade 4 and 5 titanium implant materials. After loading the implant and abutment assemblies with up to 500 N, the resulting deformations in length and diameter as well as the reverse-torque of the fixing screw were measured. No significant differences were observed between the results when the tested implant and abutment material was either Grade 4 or 5. Additionally, dynamic compression tests were performed on Grade 4 samples with different conical angles (30°, 45° and 60°). The relative changes in length (strain) of the assembly were determined over 30,000 cycles due to force varying periodically between 100 and 400 N. The reverse torques were also measured after the dynamic loading. The static and dynamic compression tests showed the same trend for different cone angles. Impression of the abutment into the dental implant was observed for lower conical angle connections. On the other hand, lower strain values were observed at larger conical angles. The reverse torque values of the fixing screws were only the half of the forward torque in case of lower conical angles, while high stability was observed with the larger conical angle connections (~ 20-30% reduction in torque). In summary, it is recommended to use a higher angle of the conical connection in order to avoid larger deformations in the lengths and diameters of the assembled implant and abutment system, as well as a significant reduction in the torque of the fixing screw.

Keywords: titanium implant; dynamic load; static load; conical angle, implant-abutment connection, screw loosening

1. INTRODUCTION

Titanium (Ti) has become a commonly used alloplastic material, due to its excellent biomechanical properties. Dental implants, which are used to replace missing tooth roots, have been performing well in clinical applications for decades [1]. Implant supported fixed partial dentures provide a similar aesthetic appearance to natural teeth and the restorations anchored on implants have no detrimental effect on adjacent teeth [2]. The load transmission mechanism of dental implants is considerably different from that of natural teeth, where periodontal ligaments play an important role in the stress-absorbing capacity [3]. Stress

DOI: https://doi.org/10.14232/analecta.2023.3.1-12

reduction – similar to that of periodontal ligaments – is not present in osseointegrated implants, and therefore occlusal loads are transmitted directly to the jaw bone. The daily loading in the oral environment leads to micro-movements in the connection, reversible then irreversible changes in the shape of the implant, micron-sized ruptures and then fractures in the implant and the connected elements, in addition to bone resorption, which may lead to peri-implant bone defects and even implant loss [4, 5]. Therefore, application of an appropriate implant-abutment connection and mechanical testing prior to clinical application is of paramount importance. The relationship between the implant and the abutment is usually described as an internal or external relationship. The distinguishing factor separating the two groups is the presence or absence of a geometric element extending above the coronal surface of the implant. The connection may also be described as a sliding fit, where there is a small space between the mating parts and the connection is passive, or a friction fit, where there is no space between the mating parts and the parts are literally forced together. The mating surfaces may include rotational resistance and indexing and/or lateral stabilizing geometry. This geometry is hereafter described as octagonal, hexagonal, tapered, tapered hexagonal, cylindrical hexagonal, spindle, cam, cam tube and pin/spigot. New generation implants mostly have an internal conical connection, although the angle of taper varies substantially. From a mechanical aspect there is still no clear determination about the ideal taper angle for the implant-abutment connection.

Grade 4 (commercially pure Ti) and Grade 5 Ti are commonly used materials for dental implants, although there are pronounced differences between their mechanical properties. Grade 4 Ti is a relatively soft and ductile metal, which makes it easy to machine and shape into dental implants. Grade 4 Ti has a lower tensile strength than Grade 5 Ti, however it is still strong enough for most dental applications and has a higher biocompatibility compared to Grade 5 Ti [6]. Grade 5 Ti (Ti-6Al-4V) is an alloy that contains aluminium (Al; ~6%) and vanadium (V; ~4%) is stronger and more durable than Grade 4 Ti. Grade 5 Ti has a higher ultimate tensile strength (~950 MPa) than Grade 4 Ti (~550 MPa). Several publications discuss that Ti raw materials are tough and resistant to plastic deformation [7,8].

The main goal of dental implant design is to achieve efficient bone-shaping-properties required by the bone quality, mechanical stability and ensure a strong bone–to-implant-contact and osseointegration [9]. The implant failure rate due to static and dynamic loads is 32% for implants with inadequate initial stability [10-14]. It is therefore critical to estimate the potential for failure in a given dental implant design. Experimental mechanical testing of dental implants provides useful data for clinicians, physicists and engineers. The load is transmitted from the prosthesis to the implant and surrounding bone. The transmission of forces and stress distribution are influenced by a number of factors, such as occlusion, abutment design, fit and the micromovements of the crown and the abutment, implant-abutment connection, implant platform, thread design at the implant neck, implant body design, number and location of implants, inclination and osseointegration of implants, and finally, the quantity and quality of bone [15].

Static and dynamic mechanical measurements should be performed to estimate the long-term success of a given implant system. The design of the connection should ensure that the reverse torque is not lowered due to the occlusal forces, however, the loosening of the screws is a very common problem [16,17]. In addition to the differences in the raw material and the cone angles, the manufacturing parameters and the dimensional accuracy of the manufactured products also play an important role [18].

The aim of our study was to investigate the mechanical stability of the conical connected dental implant and abutment assemblies with different internal cone angle values, using static and dynamic compression load tests. The following research questions arose in our study: *i) D*oes the value of the cone angle affect the screw loosening due to external forces and what degree of conicity is ideal for mechanical stability? *ii)* How does the material of the implant (grade 4 and 5) influence the mechanical behaviour, do reversible or irreversible deformations of the implants occur? *iii)* What extent the inaccuracy of the taper angles (positive and negative tolerance) affects the geometry of the implant and abutment assemblies? These sets of succeeding questions are not yet systematically investigated.

DOI: https://doi.org/10.14232/analecta.2023.3.1-12

Analecta Technica Szegedinensia

Vol. 17, No. 3 ISSN 2064-7964 2023

2. MATERIALS AND METHODS

2.1. Instruments and implant models

Static compression load tests were performed with a self-developed loading machine (Fig. 1), while the dynamic tests were performed with an all-electric dynamic test instrument (Instron ElectroPuls E3000, Norwood, MA, USA).

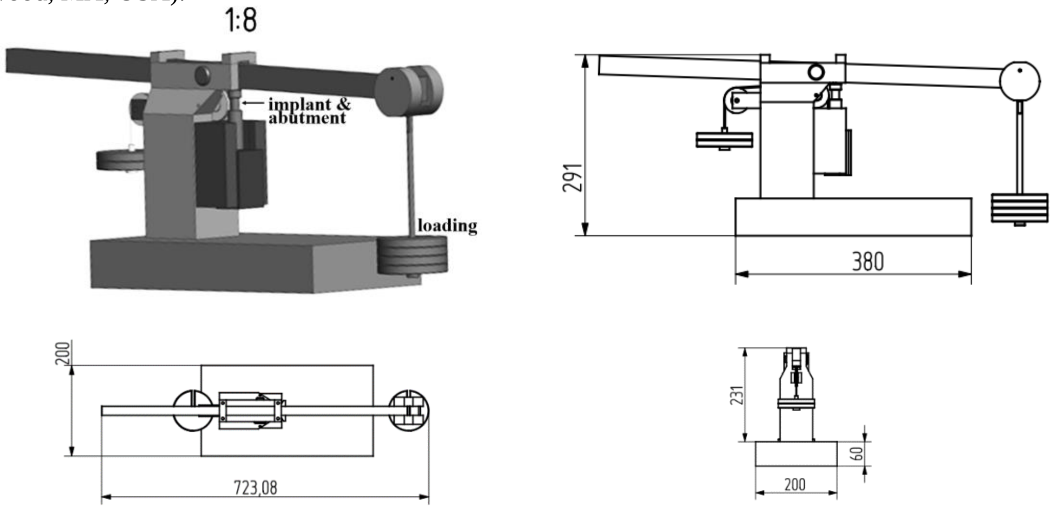

Figure 1. Technical drawings of the loading machine developed by the authors. The one-arm lifter with a lever ratio of 1:8 is loaded by cylinders with a weight of 1.25 kg each. The resulting compression force may be set between 0 N and 500 N.

The implant models and abutments were manufactured by Denti System Ltd. (Szentes, Hungary), an example is shown in Fig. 2. For the static load test, the abutments and implant body models were made from Grade 4 and Grade 5 Ti materials, 3.4 and 3.8 mm in diameter, with the following cone angles: 35°, 55°, 75°, and 90°. A total of *n*=84 abutment-implant assemblies were used for static load tests with at least 3 samples were tested using the same parameter set. For the dynamic load test abutments and implant bodies were prepared from Grade 4 Ti in 3.4 mm diameter with the following cone angles: 30°, 45° and 60°. A total of *n*=21 implant samples were used for dynamic load tests. To measure forward and reverse torque values a BMS MS150 electric torque screwdriver (BMS Torque Solutions, Ireland) was used.

Figure 2. Pictures of a test implant and abutment used in the study

DOI: https://doi.org/10.14232/analecta.2023.3.1-12

2.2. Static load test protocol

Static load tests were performed with a self-developed loading machine at the Faculty of Dentistry, University of Szeged. Static load tests were performed on a minimum of 3 samples per group. At the onset of the protocol, implants and the according abutments were assembled without tightening the fixing screw. The height of this assembly and the diameter of the implant neck were measured and recorded. After this, the fixing screw was fastened with 35 Ncm torque. Static compression loads were then applied. The choice of the load was based on the amount of mastication force applied to a tooth. The specimens were subjected to a successive load increase. The steps were 100-200-300-400-450-500 N (100 N corresponds to 10 kg weight). Each loading step was lasted for 60 s. The lengths of the implant-abutment assemblies were measured after each step of compression. After the 300N and 500 N loading the implant neck diameter was measured again. After completing the static compression load test, the fixing screw connecting the implant to the abutment was untwisted and the extension torque values were measured. The implants and abutment were reassembled without tightening the fixing screw and the total length and diameter were measured. Then the connection was then fixed by tightening the fixing screw to 35 Ncm torque again and the length of the abutment implant assembly was measured. After 60 seconds the fixing screw was tightened again and the reverse torque value was measured after 24 hours.

2.3. Dynamic load test protocol

Dynamic load tests were performed by an all-electric dynamic test instrument (Instron ElectroPuls E3000, Norwood, MA, USA) at the Faculty of Dentistry, University of Szeged (see Fig. 3 for experimental setup). Dynamic load tests were performed on a minimum of 7 samples per group. Based on our previous measurements [19], abutment implant assemblies from Grade IV Ti with different conical angles (30°, 45° and 60°) were included for further fatigue tests. For each assembly, the protocol was initiated with tightening the fixing screw between the abutment and the implant with 35 Ncm torque. Following this, the assemblies were put under loads. In the first phase 250 N load over 10 seconds was applied on the implant abutment. The dynamic load test started after this phase. During the dynamic load test a periodic force with 150 N amplitude sine wave was applied with 15 Hz frequency. This results in a force that varies dynamically over time between 100 N and 400 N. The dynamic compression test lasted 30000 cycles, after which, the 250 N loading force was released over another 10 seconds to 0 N. The device sets the force values over time and records the position of the loading head. From these values compression force-strain graphs can be prepared.

DOI: https://doi.org/10.14232/analecta.2023.3.1-12

Analecta Technica Szegedinensia
Vol. 17, No. 3 ISSN 2064-7964 2023

Figure 3. Mechanical fatigue testing machine used during the experiments and the setup of the dynamic load test. The loading head of the machine was perpendicular to the top surface of the implant head.

2.4. Inaccuracies due to manufacturing parameters

The mechanical parameters of the abutment implant models used in the study, as well as their parameter tolerances, have a significant impact on their performance. The abutments and implant models used in our study were designed using the Creo Parametric 5.0 software. As part of our investigation – with the help of this design software – implants and according abutment parts were drawn with the acceptable tolerances of the parameters. With the help of the software the tight fit case of the assembly was compared with the manufactured extreme, but still tolerated fit case. Following this, the length differences were determined between the cases of abutment and implant elements manufactured with the worst tolerance value in the opposite direction and the ideal, precisely sized abutment implant assemblies.

2.5. Statistical analysis

Statistical analysis was performed using Microsoft Excel (Microsoft Corp., Redmond, WA, USA) and SPSS Statistics 23.0 software (IBM Corp., Somers, NY, USA). Descriptive statistics of the measurements were presented as mean ± SEM (standard error of the mean). Linear regression analysis was performed on the measured data with fit equations and coefficient of determination (R^2) values. One-way analysis of variance (ANOVA) followed by Tukey HSD post hoc tests were performed. The significance level was set as 5% (p<0.05).

3. RESULTS AND DISCUSSION

3.1. Static load results

During the static mechanical loading tests, the lengths of the abutment implant assemblies were measured after applying 0, 100, 200, 300, 400, 450 and 500 N compression forces; the results of these measurements can be seen in Fig. 4. Overall, no significant differences were shown between the behaviours of implants from Grade 4 and Grade 5 raw materials in the case of connections with different taper angles (35°: p=0.562; 55°: p=0.666; 75°: p=0.235; 90° p=0.944). The largest strain was obtained for the 35° angle connections, for both Grade 4 and Grade 5 assemblies, respectively, as can be clearly seen in Fig. 4.

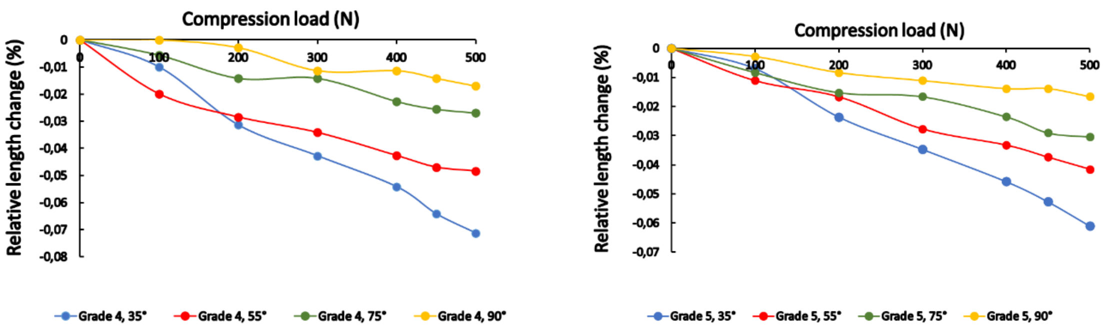

Figure 4. Relative length changes for Grade 4 and Grade 5 Ti implants after different static loads

After the application of 500 N compression load, the reverse torque was measured upon disassembling the implant and abutment parts; the results are presented in Fig. 5., with a comparison of Grade 4 and Grade 5 implants. Overall, reverse torque values consistently increased with the conical angle, i.e., the lower values were observed for the 35° conical angle case, while the highest for the 90° case. On the other

DOI: https://doi.org/10.14232/analecta.2023.3.1-12

hand, no significant differences were noted when comparing the reverse torque values of Grade 4 and 5 implants with the same conical angle (p>0.05).

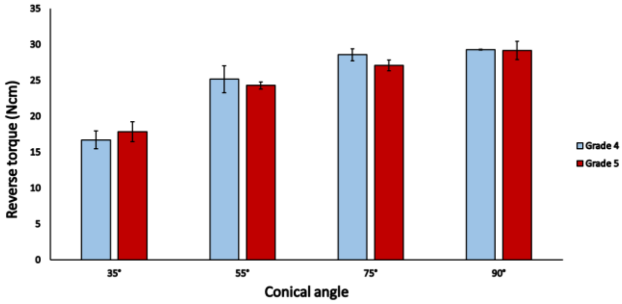

Figure 5. Reverse torque (mean ± SEM) values in case of Grade 4 and Grade 5 Ti implants with different conical angle cases (35°, 55°, 75°, and 90°)

Diameter changes of the implant models corresponding to different loads (0, 300, 500 N) were examined, during which, diameter values were measured at three locations. Figs. 6a-b and Figs. 6c-d show the relative diameter change for the Grade 4 and Grade 5 3.45 mm and 3.8 mm diameter implant models, respectively (where each data point represents the average value of 6 samples). No significant differences were found between the case of the different Ti grades.

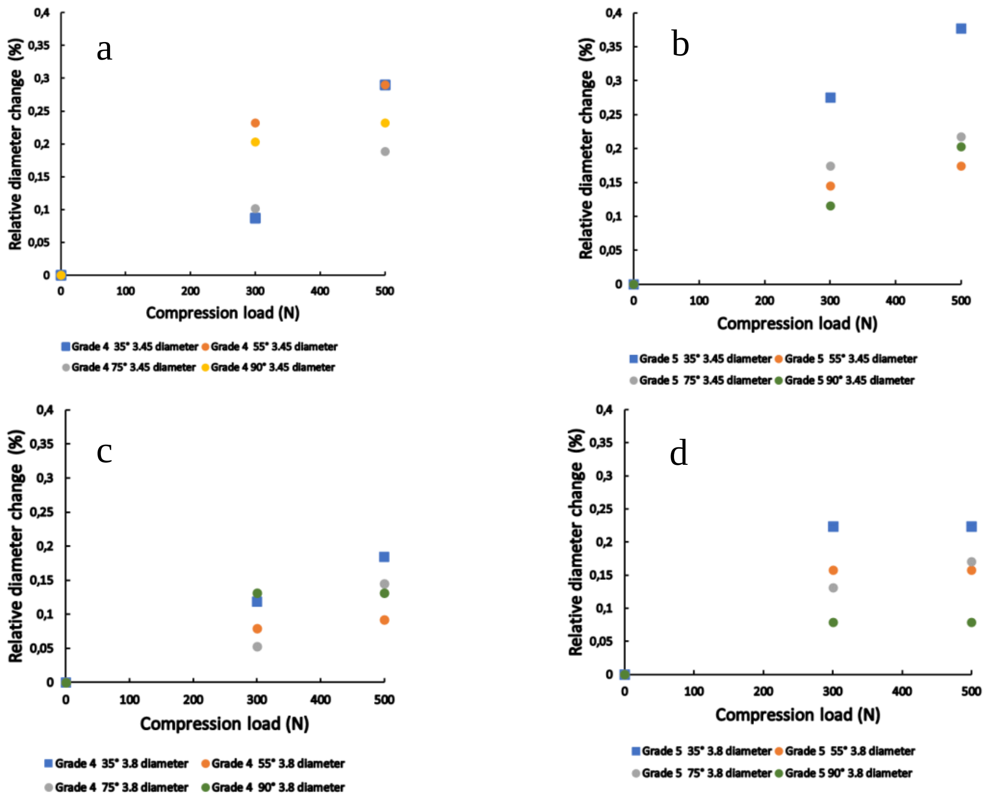

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Figure 6. Relative diameter changes of the Grade 4 and Grade 5, Ø 3.45 mm and Ø 3.8 mm Ti implants under different static compression loads, corresponding to the tested internal taper contact angles (35°, 55°, 75°, and 90°)

3.2. Dynamic load results

During the dynamic load test, the fatigue testing machine recorded the loading head position from which, compression strain of the implants with different conical angles (30°, 45° and 60°) can be determined. It was observed that there is a permanent deformation in the material, as the loading and unloading curves did not coincide. However, due to the elastic properties during the unloading phase, the material can still partially recover its length. It was also studied whether there were any differences in the impression of the implant head into the implant body during the fatigue cycles. Fig. 7 indicates that the implant head and the implant moved indeed closer together. The loading-unloading nature of this test revealed that most of the impression occur in the very first cycles, while it remains constant in the subsequent cycles; this is shown as the curves immediately begin to shift to larger displacement values, and after that there is no essential change between the loading-unloading cycles. Thus, the samples suffered elastic deformation mainly after this early phase.

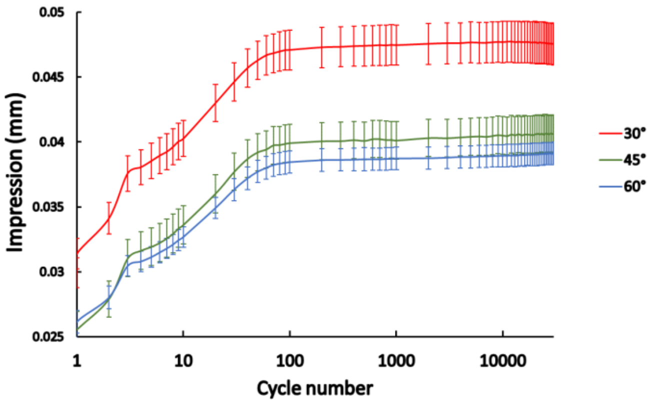

Figure 7. Mean impression levels of the implant head into the implant over the dynamic load test cycles. Sampling was carried out more frequently in the early phase of the test, while in the later stages, sampling was done in every 1000 cycles.

Final displacement values – indicating irreversible impressions of the abutments into the implant bodies – were also measured with the dynamic testing machine, following the dynamic test, as shown in Fig. 8. The highest impression value was measured for the 30° case (0.047± 0.002 mm), while the lowest value was found in the 60° case (0.039±0.001 mm), respectively; observed differences between the conical angle groups were statistically significant (p<0.001).

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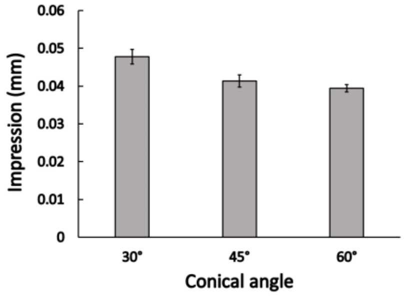

Figure 8. Displacement values (mean ± SEM) measured for each conical angle group (30°, 45° and 60°) after the fatigue test

After the dynamic loading test, reverse torque values were also measured upon disassembling the implant head and implant body; the resulting reverse torque values are shown in Fig. 9. Similar observations were obtained to our previous measurement, the lowest torque values were shown in for the 30° conical angle case, while the highest were seen for 60°; significant differences were noted among the mean reverse torque values; significant differences were observed between the average torque (p=0.003) in case of 30° (18.7 ± 1.01 Ncm), 45° (21.25 ± 0.67 Ncm) and 60° (24.03 ± 0.59 Ncm). Additionally, based on post hoc test, a significant difference between the 30° and 60° conical connections (p=0.043) was verified, while this was not the case for the 30° vs. 45° and 45° vs. 60° comparisons.

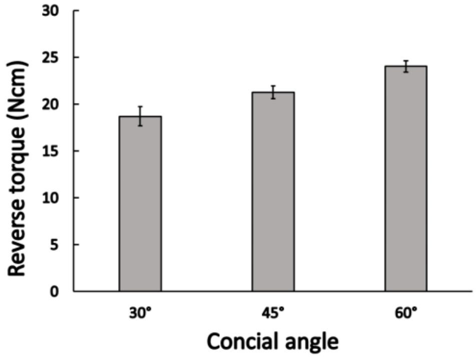

Figure 9. Reverse torque (mean ± SEM) measured for each conical angle group (30°, 45° and 60°) upon disassembling the implant head and implant after the fatigue tests

3.3. Inaccuracies due to manufacturing parameters

For the implants in our samples, a taper angle tolerance of +0/-0.5° was accepted; however, during the production of the samples, we strived to be close to 0 degrees. For the abutments, the same tolerance of 0/+0.5° was acceptable (see Fig. 10).

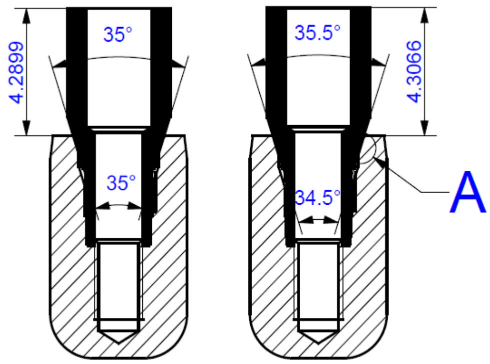

Figure 10. Schematic drawing of the conical implant and abutment head, marked with the angles and lengths.

Adjusting the tolerances in the worst possible mating, we determined the height differences from the perfectly fitting assembled abutment and implant parts, which are summarized in Table 1.

Table 1. Implant abutment height difference for conical angles with opposite tolerances for the abutment and implant parts

Ideal connection angle	Negative tolerance of the implant cone angle	Positive tolerance of the abutment cone angle	Resulting height difference from ideal connection [mm]
24°	23.5°	24.5°	0.0271
35°	34.5°	35.5°	0.0167
55°	54.5°	55.5°	0.0071
75°	74.5°	75.5°	0.0041
90°	89.5°	90.5°	0.003

From the results presented in Table 1. it can be seen, that the height of the assembled abutment and implant differs from the optimal situation if one suspects the errors resulting from the negative tolerance of the implant and positive tolerance of the abutment cone angles. As the cone angle increases the height difference decreases significantly. This calculation serves with an explanation about the reasons of the measured phenomena, namely that applying higher conical angles results in lower impressions (c.f. Fig. 8.)

3.4. Discussion, Clinical relevance of results

In our study, both the static and dynamic measurements showed similar results. Conical closure was clearly visible in the case of the implant-abutment connection with different tapers. There is also a dependence in the case of the reverse torque, i.e., the larger the cone angle of the connection, the greater the reverse torque value we measured. The static measurements resulted in that the smaller the cone angle between the implant and the abutment, the greater the diameter increase of the implant at the conical closure under load. As a result, the mechanical stress value of the implant body on the bone will be higher, i.e., more stress is transferred to the bone, which may lead to increased bone resorption rates.

T. Paepoemsin *et al.* conducted a study in which the removal torque of three different types of fixing screws was evaluated after mechanical cyclic loading [20]. In their paper, they worked with flat head and conical screws, and then compared the reverse torques of each group after 1 million cycles after the first 10 minutes of dynamic loading. When comparing the measured reverse torque with the results of the first 10-minute dynamic load test and after 1 million cycles, a significant decrease was shown. Our results also

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indicated that a change occurred during the dynamic loading test that reduced the tension of the implant abutment head.

Benjaboonyazit *et al.* also studied the formation of loose connections due to fatigue [21]. In their report, 3.75 mm Octatorx taper implants were used and the screws were tightened to 30 Ncm, followed by a very long dynamic loading test of 2 million cycles, and then the removal torque values were compared. Their results are also consistent with our results, i.e. they obtained a reverse torque value of over 27 Ncm without load, which decreased to below 16 Ncm after their fatigue test protocol. Our study showed that the reduction of the reverse torque can be moderated with an increased taper angle. Comparing the static 55° results, which resulted in a reverse torque of 24-25 Ncm, after the dynamic load test, the 60° case decreased to very similar values, i.e. around 24 Ncm. These results also highlighted that increasing the taper angle does indeed promote stronger grip for longer periods of time, even under intermittent loads.

Joo-Hee and Hyun-Suk also performed cyclic loading on Grade 4 Ti implants with an external hexagonal connection [22]. Following the ISO protocol, the implants were inserted at an angle of 30°. After 1 million cycles, the reverse torque was measured at 15.2 Ncm at 300 N (equivalent to 30 kg); we also determined the torque values before the dynamic test, which was 25.2 Ncm. Their results coincide with the results of the present study, in their case the reduction of the reverse torque was approximately 40% compared to the pre-post dynamic test. The referenced articles support the results of our tests, i.e. under loading, the greater the angle of the implant-abutment-connection was, the smaller the amount of screw loosening could be measured.

Screw loosening of taper-connected implants (i.e., a loose state of the clip between the implant and the fixing screw) may be an important clinical problem, as it increases the risk of denture removal and screw failure. Screw loosening of implants may be due to various reasons, such as incorrect tension of the screw, excessive load on the screw, a defect in the material or size of the fixation screw, wear between the implant and the fixation screw, or continuous slippage of the screw due to continuous loading. Therefore, properly securing the implant and fixing screw and inspecting the abutment stability in the implant by the dentists is critical. Reversible and irreversible shape deformations of Ti implants may have a significant impact on the success of the implant surgery and the long-term stability of the implant. In reversible deformation, deformation occurs during surgery or subsequent loading (mastication) due to the elasticity of the Ti implant, but the implant returns to its original shape when the load is removed. This type of shape deformation is usually associated with micro- and macro-deformations due to loading, which may lead to fatigue fracture in the long term. During irreversible shape deformation, the implant does not return to its original shape, even after the load is removed; this is usually due to exceeding the yield point or excessive deformation during surgery. Irreversible deformation may have a serious effect on the stability of the implant, as the shape of the implant changes and, as a result, the implant does not fit properly with the implant bed. In order to prevent irreversible deformity, dentists must be careful to choose the right size and shape of implant and carefully plan and perform surgical procedures. Planning, with pre-planning and simulation, plays an important role in selecting the right sized and shaped implants for the patient and ensuring the correct fit of the implant to the implant bed. Performing professional procedures and using appropriately chosen implants may reduce the risk of irreversible shape deformations and improve the long-term stability of the implants. The inaccuracy of the taper angles of the implant and the abutment has a considerable influence on the compression under load. The greater the dimensional error from manufacturing, the greater the impression of the abutment into the implant body along the conical surfaces.

In this research, a systematic study was performed to investigate the role of the conical angle during static and dynamic load tests. Furthermore, the influence of the implant and abutment material (i.e. Grade 4 and 5) was also investigated in case of static compression measurements. During the investigations, we compared the influence of the angle of conical connections on the reverse torque values. To the best of our knowledge, such publication was not yet published, where these parameters were comprehensively assessed. The results found in the literature partially overlap with ours, but did not cover all parameters of our investigations.

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4. CONCLUSIONS

In this study, mechanical testing of assembled abutments and implants demonstrated that increasing the conical angle of the connection decreases permanent strain values. Static compression experiments revealed that there are no significant differences in reverse torque between Grade 4 and Grade 5 abutment and implant assemblies that share the same conical angle. In summary, it is recommended to use a connection with a higher taper angle in order to avoid major deformations of the lengths and diameters of the implant at the connection and a significant reduction in the torque of the fixing screw. Our results may contribute to understanding the long-term success of dental implants.

5. ACKNOWLEDGEMENTS

The authors are thankful for the support of the Study Group for Dental Research Methodology and Health Sciences, University of Szeged. This work was supported by the grant GINOP-2.2.1-15-2017-00039.

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