Stability of the Implant/Abutment Joint in a Single-Tooth External-Hexagon Implant System: Clinical and Mechanical Review

Ameen Khraisat, BDS, PhD;* Osama Abu-Hammad, BDS, MSc, PhD;† Awni M. Al-Kayed, DDS, PhD;† Najla Dar-Odeh, BDS, FDS RCS(Ed)‡

ABSTRACT

Rigorous efforts have recently been made to reduce the recurrence of implant/abutment joint failure in single-tooth implant restorations. However, the current knowledge about the stability of implant/abutment joints in an external hexagon implant system is incomplete. We reviewed clinical data regarding single-tooth implant treatment with Brånemark implants, specifically the CeraOne® abutment system (Nobel Biocare AB, Göteborg, Sweden). In vitro studies on joint stability were systematically assessed. Bending overload and the presence of misfit at the implant/abutment joint interface are the critical mechanical conditions that can make the joint unstable. Appropriate joint fitness and proper alignment of the implant should be assessed, and occlusal adjustment by narrowing the restoration width and flattening cuspal inclination should be applied to avoid bending moments caused by the lateral component of occlusal forces. Sufficient clinical reports of longer duration that evaluate and verify longer-term success of the newly manufactured joint components were unavailable.

KEY WORDS: abutment screw, embedment relaxation, external hexagon implant, fatigue, implant abutment interface, misfit, preload, screw loosening, settling

Application of the 0.7 mm external-hexagon implant (introduced in the Brånemark System [Nobel Biocare AB, Göteborg, Sweden]) to patients who are missing a single tooth has increased in clinical practice.[1–15] This application allows the crowns to be cemented directly onto the implant abutment, and the abutment can be modified in the laboratory or even in the patient's mouth.[16,17] However, implant/abutment joint instability (specifically, abutment screw loosening and/or fracture) in single-tooth implant restorations is a commonly encountered complication.[2,4,10,13] Clinicians and manufacturers have made rigorous efforts to reduce the recurrence of this problem.[18–24] For the Brånemark implant system, the manufacturer kept the implant external hexagon whereas the titanium abutment screw was replaced by a gold alloy screw with a new design. The latter allows a higher tightening torque and thus a greater preload that keeps the implant/abutment joint more stable. Other attempts by the manufacturer were made through adding antirotational elements or designs to the implant components, particularly to the implant/abutment joint. The maker of Steri-Oss® (Nobel Biocare USA, Yorba Linda, CA, USA) has adopted a 1 mm external hexagon on the abutment system as an antirotational element. In an attempt to eliminate rotational misfit at the implant/abutment joint, the manufacturer of the Spline™ implant (Sulzer Calcitek Inc, Carlsbad, CA, USA) has produced the "close-sliding fit" for a stronger and more stable joint.[25]

*Assistant professor, Department of Conservative Dentistry and Prosthodontics, Faculty of Dentistry, University of Jordan, Amman, Jordan; †associate professor, Department of Conservative Dentistry and Prosthodontics, Faculty of Dentistry, University of Jordan, Amman, Jordan; ‡assistant professor, Department of Oral and Maxillofacial Surgery, Oral Medicine, and Periodontics, Faculty of Dentistry, University of Jordan, Amman, Jordan

Reprint requests: Dr. Ameen Khraisat, Alameryah Suburb, Al-Balqa Islamic School Street, Salt P.O.B. 436, Jordan; e-mail: khraisat@lycos.com

From a mechanical point of view, two important factors may be described as major elements in external-hexagon implant/abutment joint stability: the screw joint preload, and the antirotational element.

PRELOAD

Abutment screw preload is defined as the tensile force that is built up in the screw from the head to the threads as a product of screw tightening.[18,26–28] It creates a compressive (contact) force at the abutment–screw head, abutment-implant, and abutment screw–implant mating thread interfaces. Preload depends primarily on the applied torque and secondarily on the component material, the design of the screw head and thread, and surface roughness. The magnitude of the applied torque is limited by the screw's yield strength and the strength of the bone-implant interface that is the biologic limit of the applied torque.[29,30] Animal studies suggest that the applied torque to the bone-implant interface should be within 30 to 35 Ncm.[31]

Relationship between Applied Torque and Preload

Several authors[32–36] have discussed the relationship between applied torque and preload. The influence of frictional forces make torque and preload indirectly proportional to one another.[34] Some of the factors that the coefficient of friction depends on are the hardness of the threads, the surface finish, the presence of lubricant, and the speed of tightening. The coefficient of friction increases with increasing hardness of the material, surface roughness, dryness of situation, and speed of tightening. In addition, geometry and material properties may affect the coefficient of friction to a lesser extent.[34] Motash reported that only 10% of the torque applied to the initial tightening of a screw system remains to induce preload whereas 90% is used to overcome friction between the mating components.[37] This means that a small difference in applied torque may have a major effect on preload.[38] Moreover, repeated cycles of tightening and loosening were found to decrease thread friction during torque application. This is because of burnishing of the microroughness at the contacting surfaces, which consequently increases the axial preload levels.[37] Studies comparing preload between as-received and finished mating-surface abutments reported preloads of 97 N[39] and 322 N,[40] respectively. Preload is reduced when applied torque is used to overcome friction and to flatten rough mating surfaces rather than to elongate the screw and generate preload. Rigorous efforts have been made to reduce the recurrence of this phenomenon. For instance, Implant Innovations Inc. (Palm Beach Gardens, FL, USA) added a solid-lubricant thin-gold coating to the abutment screw surface (Gold-Tite™ abutment screw) to decrease the coefficient of friction on torque application and to increase preload values.[41,42] Another example is the Steri-Oss implant system (Nobel Biocare USA, Yorba Linda, CA, USA), which adopted a new surface technology (Torq Tite™) for the titanium abutment screw in order to decrease friction on torque application and to prolong fatigue life.[43]

Burguete and colleagues[34] highlighted two major aims for tightening screwed joints in the implant system. First, the joint components must be clamped together by applying a recommended torque on the joint screw. For this to be achieved, an optimum preload should be applied, providing a practical level of protection against loosening and providing a more stable anchorage. The abutment screw should be thought of as a "spring." When torque is applied, the "spring" elongates and places the shank and threads into tension. The elastic recovery of the screw creates the clamping force that brings the joint components together.[34,44] The second major aim is to prolong the screw's fatigue life. The greater the preload applied to the screw (up to 60% of the ultimate tensile strength),[26] the longer will be the screw's fatigue life. Junker and Wallace[45] highlighted the same implication for eccentrically loaded threaded joints. However, when the total of the preload and the external forces goes above the yield strength of the screw, the screw becomes plastically deformed, and the joint starts to open. Consequently fatigue performance drops drastically, and the screw joint fails. In addition the clamping effect is lost when the axial compressive load on the abutment exceeds the clamping force.[44]

Rodkey[46] described the phenomenon of screw loosening by the following sequence. Once the functional loads are applied, the mating surfaces are compressed against each other, thereby reducing the frictional forces between the threads. Consequently the clamping effect will be lost. When the threads disengage and the preload declines, the screw loosens. Bickford[38] described the screw joint failure as occurring in two stages. In the initial phase the applied external forces cause small slippages between the mating threads, resulting in a reduction of the frictional forces in the threads, and some of the preload is thereby lost. At this phase the only way for the joint to resist slippage is to have a maximum preload up to the ultimate strength that offers greater friction forces so that a larger force is required to cause slippage. In the second phase the external force rapidly erodes the remaining preload because of vibration and micromovement that cause the threads to "back off" and consequently diminish the ability of the screw to sustain joint stability. Once this stage has been reached, the screw joint has failed.

Factors Affecting the Reduction of Preload on the Abutment Screw

The complexity of abutment screw loosening has made it difficult for many researchers to specify causes of this problem. The loosening problem was generally attributed to the complexity of masticatory loading conditions since they can induce varying and complex stresses throughout the implant restorations.[47,48] Some possible causative factors that affect the reduction of the preload on the screw and thus screw joint instability are described in the following text.

Bending Overload. Bending is a critical load situation that can make the screw joint unstable. A bending force larger than the yield strength of the screw results in plastic deformation that leads to preload loss. The yielding point of a gold alloy screw is 1,370 N, calculated according to screw dimensions and material specifications.[18]

Fatigue. Fatigue is the progressive crack propagation that finally results in a catastrophic fracture under repeated loading below the yield stress.[49] In implant systems dynamic fatigue occurs when cyclic loading is applied to the system at a level below the yield strength of the abutment screw material. Versluis and colleagues[50] reported that the abutment screw might loosen or fracture when fatigued or overloaded. In their report fatigue was a major possible cause of preload loss and implant/abutment joint instability.

In a theoretical analysis, Patterson and Johns[51] reported two locations that are likely sites for the initiation of fatigue failure in the abutment screw. The first is at the change of section between the shank and the screw head. The second, where the highest stress concentration occurs, is at the root of the screw's first thread. The concentration of stress on the first loaded thread was explained as being a result of the different changes in thread pitch produced by the tensile strain in the bolt or screw and compressive strain in the clamped parts. This was concluded by Khraisat and colleagues,[52] who found that the first thread of the abutment screw was the site of fatigue fracture in Brånemark implants. In their study the fatigue resistance to a lateral load of 100 N was compared between two implant-abutment combinations: (1) the 4 mm Brånemark implant with a hexagon-mediated butt joint and (2) the 4.1 mm ITI Dental Implant System® implant (Straumann AG, Waldenburg, Switzerland) with an 8° internal conical-interface design (taper joint). In all tested specimens the abutment screw in the butt joint design fractured at between 1.2×10^6 and 1.7×10^6 cycles whereas the taper joint design did not fail until a defined target of 1.8×10^6 cycles.[52] In the butt joint design all failures occurred at the junction between the unthreaded and threaded parts of the abutment screw. It was postulated that the axial preload of the screw in the butt joint was the determining factor for joint stability. In particular, a misfit at the implant-abutment interface might allow micromovement of the abutment screw, leading to the increase of its tensile stress and thus the decrease of its preload.

Settling, or Embedment Relaxation. Several authors have discussed embedment relaxation as a major mechanism of screw loosening.[18,37,53–56] Embedment relaxation might be defined as wear or flattening of the microscopically rough high spots at the contacting surfaces, caused by micromovement when the joint is subjected to external loads and vibrations. This effect is based on the facts that no surface is completely smooth and that every machined surface exhibits some degree of microroughness. Wear (of a nonabrasive type) at the contact areas may bring the two surfaces closer to each other. Therefore, when the total settling effect exceeds the elastic elongation of the screw, the screw loosens owing to the loss of tension in the shank, and the contact forces (preload) under the head and on the threads thus cease. For this reason, it was recommended that the abutment screw be retightened after the initial insertion and periodically whenever possible for verification of proper tautness.[18,26,37,44,53–56] The magnitude of settling was described as being dependent on surface roughness, surface hardness of the implant and screw, time, and magnitude of the functional loads.[18,53] It was estimated that 2 to 10% of the initial preload is lost because of the settling effect[55]; consequently a lower torque value (compared to the initial tightening one) is required for loosening the screw.[55–59] In an attempt to reduce the settling effect, a 10-minute interval between tightening and retightening measurements was inserted according to the protocol suggested by Dixon and colleagues[57] and by Breeding and colleagues.[58]

Vibration or Damping. Junker and Wallace[45] were the first to describe a recent theory with regard to screw self-loosening. They reported that vibratory micromovements caused by shear force (specifically in the transverse plane) are responsible for screw self-loosening. Vibratory motion flexes or bends the screw, which causes a disengagement or loss of contact between the screw threads and implant internal threads, as well as at the undersurface of the screw head and the abutment body (ie, loss of preload). This explanation was supported by Bickford,[38] who explained that the direction of the functional load is not considerable as long as the load is sufficient to reduce frictional resistance between the threads and the undersurface of the screw head and thus sufficient to cause thread slippage. Intraoral shear forces occur in the last part of the closing phase and in the initial part of the opening phase during mastication as the cusps of maxillary and mandibular teeth slide along one another.[60] Moreover, in an analysis of physiologic tremor and muscle activity, Timmer and colleagues[48] stated that any muscle-controlled movement is accompanied by vibratory micromovement because of the nature of muscle unit contraction. This also applies to the masticatory muscles during mastication.[48,61] Thus implant and tooth contacts may transfer the resultant vibratory micromovements to the screw joint during jaw function, and screw self-loosening might occur as a result.[62] Many factors may affect the potential for screw self-loosening; in the oral cavity, for instance, these factors are the quality of bone and periodontal ligament, the condition of the temporomandibular joint, and the masticatory mass of the muscles. In addition, factors related to the screw itself, such as the yield strength, the screw's design and material, and the potential for fatigue, may possibly play a part in initiating screw self-loosening.[62]

Other Factors. Other factors[11,18,19,51,53,63–65] mentioned as probable contributing mechanisms of screw loosening are inadequate screw tightening, which can lead to insufficient preload generation in the abutment screw; improper screw design and/or material; a poorly machined component that leads to a poor fit; and an improperly aligned abutment and implant, which would increase the lever arm and bending moments. Finally, elasticity of bone at the implant receptor site was also believed to influence screw joint stability.[53,56,65] A significant difference in screw stability in the maxilla compared to that in the mandible was reported.[2] Greater functional deformation of maxillary cancellous bone would result in significantly more stress at the implant bone level and consequently at the implant/abutment joint.[53]

The Role of the Antirotational Element

The original purpose of this 0.7 mm hexagon extension was to provide a rotational torque-transferring mechanism that secures the implant on its mount during surgical placement into the bone at the implant receptor site. With the recent introduction of single-tooth implant applications, this purpose has been changed to the provision of a prosthesis indexing and antirotational mechanism.[26,66] Moreover, the implant hexagon extension is also used as an orientation device for the impression coping, to transfer the exact oral relationship of the implant to the working cast.[67]

The manufacturer of the Brånemark implant has stated that ''freedom of fit'' between implant components, incorporated into their design, would allow horizontal and rotational movement so that any horizontal fitting errors would be tolerated.[68] On the other hand White[69] reported that horizontal misfits can cause ''implants and their internal screw parts to deform on tightening'' and consequently affect screw joint stability. In addition, rotational misfit at the implant–abutment hexagon interface has been considered a major factor in screw joint failure.[70,71] In a study completed by Binon and McHugh,[71] the implant-abutment rotational misfit was reduced, and the specimens underwent eccentric axial cyclic loading. The results indicated a direct correlation between the implant-abutment rotational misfit and the screw loosening. The investigators concluded that the elimination of rotational misfit would make the screw joint more resistive to screw loosening. In another study conducted by Binon,[70] incrementally larger sizes of abutment hexagons with corresponding increased rotational misfits were cyclically loaded until joint failure occurred. The greater the size discrepancy, the greater the rotational misfit and the smaller the interhexagon flat-to-flat contact area at the implant-abutment interface. The study results showed a direct correlation between implant-abutment rotational misfit and screw joint failure. It was concluded that the tighter the fit between the implant hexagon extension and its abutment counterpart, the greater the number of cycles to screw joint failure. Data from the same study indicated a significant improvement in screw joint stability when the implant-abutment rotational misfit was less than 2°.[70]

Another study investigated the influence of two patterns of lateral cyclic loading on abutment screw loosening in a hexagon-mediated butt joint system.[72] In this study a lateral load of 50 N was centrically applied to the first-group specimens for 1.0×10^6 cycles whereas the same load was eccentrically applied to the second-group specimens in the untightening direction for 1.0×10^6 cycles. Before and after cyclic loading, the reverse torque of the abutment screw was measured and compared between the two loaded groups and one unloaded group (control). The data obtained indicated that the centric-loading period decreased the reverse torque significantly whereas the eccentric load affected it insignificantly. These results might be related to the presence of play at the hexagon interface, which aggravated screw fatigue in the centric-loading group. On the other hand the eccentric lateral load made the implant hexagon engage with the abutment counterpart and supplied a lock effect, which dispersed bending forces away from the abutment screw and reserved the screw torque.[72]

In an evaluation of machining accuracy and consistency, Binon[73] reported that the implant–abutment hexagon fit is important in single-tooth restorations "where exact seating is critical to attaining repeatable interproximal contacts and optimal anti-rotational characteristics." The machining tolerance of the present technology was described as reaching 3 to 5 μm with computer numeric controlled screw machines.[26] However, the tungsten carbide cutting tool can become dull and must then be replaced; the tolerances of the machined components will decrease in accuracy if the tool is not replaced.

Implant hexagon extension height has been implicated as an important factor in maintaining the antirotational stability of the screw joint.[26,66] English[26] reported that the external hexagon theoretically requires a minimum height of 1.2 mm to attain the optimal antirotational effect.

In a 3-year clinical follow-up study, 23 Brånemark single-implant restorations were placed in 16 patients.[1] It was reported that 13 of 23 (57%) abutment screws went loose in the first year, 7 of 23 (30%) abutment screws loosened during the second year, and 1 of 20 (5%) abutment screws loosened during the third year. In the same study 8 of 23 (35%) abutment screws continued functioning without loosening during the 3-year follow-up period. Another 3-year retrospective study, which used 93 Brånemark single-tooth implants in 77 patients, reported 40 (43%) cases of abutment screw loosening; 28 screws loosened once while the other 12 screws loosened two or more times during a 3-year period.[5] In a 3-year follow-up study completed by Jemt and Pettersson,[3] 70 Brånemark single-tooth implants were placed in 50 patients; 45% of the abutment screws had to be retightened at least once during the follow-up period.

In a prospective study 107 single-tooth implant restorations supported by Brånemark implants were observed for 5 years.[2,4,10] It was reported that 26% of the abutment screws were retightened during the first year. Seventeen of the abutment screws were loose at the 1-week follow-up visit, 7 were loose at 1 month, 5 were loose at 6 months, and 5 were loose at 1 year. During the third year of observation, 11% of the abutment screws loosened in 10 patients. Moreover, one titanium abutment screw fractured after 3 years, and 13 were replaced by the new gold alloy screw. Another prospective study presented the results achieved with 65 CeraOne® abutments (Nobel Biocare AB) after 5 years of loading.[11] It was concluded that tightening the new gold abutment screw to 32 Ncm in the CeraOne system eliminated the problem of screw loosening or fracture.

In fact the new gold alloy abutment screw in the CeraOne abutment significantly decreased the loosening phenomenon but did not eliminate it. A recent 5-year multicenter study of 97 single-tooth implants using the CeraOne system reported the loosening of 4 (4.1%) abutment screws.[13]

In the clinical studies mentioned above, the new gold alloy abutment screw in the CeraOne abutment significantly decreased the occurrence of screw loosening and/or fracture. This was attributed to the higher amount of frictional forces produced between the gold alloy screw and the titanium implant component. Furthermore, the tensile and yield strengths are greater for the gold alloy than for titanium; a greater preload can thus be generated in the gold screw. Jörnéus and colleagues[18] reported ultimate tensile and yield strengths of 1,450 N and 1,370 N, respectively, for the CeraOne gold alloy abutment screw. These values are more than two times those for the titanium grade 1 screw (630 N and 470 N, respectively). Ultimate tensile strength is the maximum stress that an alloy can sustain without fracture; yield strength is the measure of the alloy's resistance to plastic deformation. Yield strength is an important measurement clinically because once a restoration is deformed, it is structurally compromised and at significant risk.[26] Tan and Nicholls[32] reported a mean screw joint preload of 643.4 N for the CeraOne 2 mm gold abutment screw with a recommended tightening torque of 32 Ncm. This preload value was the highest recorded among the investigated seven external-hexagon abutment systems. In another study, McGlumphy and colleagues[33] reported a mean preload value of 539.6 N for the CeraOne abutment screw torqued to 32 Ncm. In spite of the difference between the two studies, both values are well within the safety margin of the screw fatigue life.

Finally, when the implant/abutment joint is unstable owing to any of the aforementioned factors, deleterious complications may occur. Gap creation at the abutment screw–abutment interface,[74] loosening or fracture of the abutment screw,[75] implant fatigue or fracture,[19] marginal bone loss,[76,77] and bone fracture[78] were reported as results of an unstable implant/abutment joint.

Because single-molar implants might have a high susceptibility to bending overload and shearing stress at the implant/abutment screw joint,[5,8,19,22,37,79,80] a number of guidelines were suggested for better stability,[19,22,61–63,79–86] such as (1) placing the implant in a location such that the occlusal loads are directed alongside the longitudinal axis of the implant, (2) centering the occlusal contact (for the reason mentioned above), and (3) flattening the cuspal inclination, to decrease bending moments caused by the lateral component of occlusal forces as well as intraoral shear forces that cause vibration. Other guidelines were also suggested,[79–86] such as narrowing the buccolingual and mesiodistal widths of the restoration (ie, reducing cantilevers and the consequent bending moments) and properly tightening the abutment screw for optimal preload generation in the screw shaft, thus obtaining a favorable joint stability.

REFERENCES

1. Jemt T, Lekholm U, Grödahl K. A three–year follow-up study of early single implant restorations ad modum Brånemark. Int J Oral Maxillofac Implants 1990; 5:341–349.
2. Jemt T, Laney WR, Harris D, et al. Osseointegrated implants for single-tooth replacement. A 1-year report from a multicenter prospective study. Int J Oral Maxillofac Implants 1991; 6:29–36.
3. Jemt T, Pettersson P. A 3-year follow-up study on single implant treatment. J Dent 1993; 21:203–208.
4. Laney WR, Jemt T, Harris D, et al. Osseointegrated implants for single-tooth replacement: progress report from a multicenter prospective study after 3 years. Int J Oral Maxillofac Implants 1994; 9:49–54.
5. Ekfeldt A, Carlsson GE, Börjesson G. Clinical evaluation of single-tooth restorations supported by osseointegrated implants: a retrospective study. Int J Oral Maxillofac Implants 1994; 9:179–183.
6. Andersson B, Odman P, Lindval AM, Lithner B. Single-tooth restorations supported by osseointegrated implants: results and experiences from a prospective study after 2 to 3 years. Int J Oral Maxillofac Implants 1995; 10:702–711.
7. Becker W, Becker BE. Replacement of maxillary and mandibular molars with single endosseous implant restorations: a retrospective study. J Prosthet Dent 1995; 74:51–55.
8. Hass R, Mensdroff-Pouilly N, Mailath G, Watzek G. Brånemark single tooth implant: a preliminary report of 76 implants. J Prosthet Dent 1995; 73:274–279.
9. Avivi-Arber L, Zarb GA. Clinical effectiveness of implant-supported single tooth replacement: the Toronto Study. Int J Oral Maxillofac Implants 1996; 11:311–321.
10. Henry PJ, Laney WR, Jemt T, et al. Osseointegrated implants for single-tooth replacement: a prospective 5-year multicenter study. Int J Oral Maxillofac Implants 1996; 11:450–455.
11. Andersson B, Ödman P, Lindvall A-M, Brånemark P-I. Cemented single crowns on osseointegrated implants after 5 years: results from a prospective study on CeraOne. Int J Prosthodont 1998; 11:212–218.
12. Andersson B, Ödman P, Lindvall A-M, Brånemark P-I. Five-year prospective study of prosthodontic and surgical single-tooth implant treatment in general practices and at a specialist clinic. Int J Prosthodont 1998; 11:351–355.
13. Scheller H, Urgell JP, Kultje C, et al. A 5-year multicenter study on implant-supported single crown restoration. Int J Oral Maxillofac Implant 1998; 13:212–218.

14. Wannfors K, Smedberg J-I. A prospective clinical evaluation of different single-tooth restoration designs on osseointegrated implants. A 3-year follow-up of Brånemark implants. Clin Oral Implants Res 1999; 10:453–458.
15. Grunder U. Stability of the mucosal topography around single-tooth implants and adjacent teeth: 1-year results. Int J Periodontics Restorative Dent 2000; 20:11–17.
16. Chee W, Felton DA, Johnson PF, Sullivan DY. Cement versus screw-retained prostheses: which is better? Int J Oral Maxillofac Implants 1999; 14:137–141.
17. Keith SE, Miller BH, Woody RD, Higginbottom FL. Marginal discrepancy of screw-retained and metal-ceramic crowns on implant abutments. Int J Oral Maxillofac Implants 1999; 14:369–378.
18. Jörnéus L, Jemt T, Carlsson L. Loads and design of screw joints for single crowns supported by osseointegrated implants. Int J Oral Maxillofac Implants 1992; 7: 353–359.
19. Rangert B, Krogh P, Langer B, Roekel NV. Bending overload and implant fracture: a retrospective clinical analysis. Int J Oral Maxillofac Implants 1995; 10:326–334.
20. Cavazos E, Bell FA. Prevent loosening of implant abutment screws. J Prosthet Dent 1996; 75:566–569.
21. Binon PP. Evaluation of the effectiveness of a technique to prevent screw loosening. J Prosthet Dent 1998; 79:430–432.
22. Tylor TD. Prosthodontic problems and limitations associated with osseointegration. J Prosthet Dent 1998; 79: 74–78.
23. von Krammer R. Procedure for obturating the access canal and preventing the loosening of the abutment screw in an implant-retained fixed prosthesis. J Prosthet Dent 1999; 81:234–236.
24. Artzi Z, Dreiangel A. A screw lock for single-tooth implant superstructures. J Am Dent Assoc 1999; 130:677–682.
25. Binon PP. The spline implant: design, engineering, and evaluation. Int J Prosthodont 1996; 9:419–433.
26. English CE. Externally hexed implants, abutments, and transfer devices: a comprehensive overview. Implant Dent 1992; 1:273–282.
27. Shigley JE. Mechanical engineering design. 3rd Ed. New York: McGraw-Hill, 1977:240–245.
28. Rangert B, Jemt T, Jörnéus L. Forces and moment on Brånemark implants. Int J Oral Maxillofac Implants 1989; 4: 241–247.
29. McGlumphy EA, Mendel DA, Holloway JA. Implant screw mechanics. Dent Clin North Am 1998; 42:71–89.
30. Tjellstrom A, Jacobson M, Albrektsson T. Removal torque of osseointegrated craniofacial implants. Int J Oral Maxillofac Implants 1988; 3:287–289.
31. Carr A, Larsen P, Papazaglou E, McGlumphy E. Reverse torque failure of screw-shaped implants in baboons: baseline data for abutment torque application. J Oral Maxillofac Surg 1995; 10:167–174.
32. Tan KB, Nicholls JI. Implant-abutment screw joint preload of 7 hex-top abutment systems. Int J Oral Maxillofac Implants 2001; 16:367–377.
33. McGlumphy EA, Kerby RE, Elfers CL. A comparison of screw preload for the single tooth implant. J Dent Res 1994; 73(Spec Issue):203. (Abstr 809)
34. Burguete RL, Johns RB, King T, Patterson EA. Tightening characteristics of screwed joints in osseointegrated dental implants. J Prosthet Dent 1992; 71:592–599.
35. Bowden FP, Gunne J, Sullivan DY. The friction and lubrication of solids. Oxford: Oxford University Press, 1950.
36. Abkowitz S, Burke JJ, Hiltz RH. Titanium in industry. New York: Van Nostrand Co. Inc., 1955.
37. Motash N. Development of design charts for bolt preloaded up to the plastic range. J Eng Ind 1976; 98:849–851.
38. Bickford JH. An introduction to the design and behavior of bolted joints. New York: Marcel Dekker, 1995:515–564.
39. Carr AB, Brunski JB, Luby ML. Preload and load-sharing of strain-gauged CP-Ti implant components. J Dent Res 1992; 71(Spec Issue):528. (Abstr 106)
40. Carr AB, Brunski JB, Labishak J, Bagley B. Preload comparison between as-received and cast-to-implant cylinders. J Dent Res 1993; 72(Spec Issue):190. (Abstr 695)
41. Porter SS, Robb TT. Increasing implant-abutment preload by thin-gold coating abutment screws. Palm Beach Gardens, FL: 3i-Implant Innovations, 1998.
42. Robb TT, Porter SS. Increasing abutment rotation by applying thin-gold coating. Palm Beach Gardens, FL: 3i-Implant Innovations, 1998.
43. Steri-Oss. Evaluation of Torq Tite surface technology. Number TR01-1148. Yorba Linda, CA: Steri-Oss Dental Care Co, 1998.
44. Haak JE, Sakaguchi RL, Sun T, Coffey JP. Elongation and preload stress in dental implant abutment screws. Int J Oral Maxillofac Implants 1995; 10:529–536.
45. Junker GH, Wallace PW. The bolted joint: economy of design through improved analysis and assembly methods. Porc Inst Mech Eng [H] 1984; 1998:255–266.
46. Rodkey E. Making fasting joints reliable... way to keep 'em tight. Assembly Eng 1977; 3:24–27.
47. Korioth TW, Hannam AG. Deformation of the human mandible during simulated tooth clenching. J Dent Res 1994; 73: 56–66.
48. Timmer J, Lauk M, Pfleger W, Deuschl G. Gross spectral analysis of physiological tremor and muscle activity. II. Application to synchronized electromyogram. Biol Cybern 1998; 78:359–368.
49. Craig RG, Powers JM. Restorative dental materials. 11th Ed. St. Louis, MO: Mosby, 2002:90–91.
50. Versluis A, Korioth TW, Cardoso AC. Numerical analysis of a dental implant system preloaded with a washer. Int J Oral Maxillofac Implants 1999; 14:337–341.
51. Patterson EA, Johns RB. Theoretical analysis of the fatigue

life of fixture screws in osseointegrated dental implants. Int J Oral Maxillofac Implants 1992; 7:26–33.
52. Khraisat A, Stegaroiu R, Nomura S, Miyakawa O. Fatigue resistance of two implant/abutment joint designs. J Prosthet Dent 2002; 88:604–610.
53. Binon P. The role of screws in implant systems. Int J Oral Maxillofac Implants 1994; 9(Suppl):48–63.
54. Jörnéus L. Screws and cylinders in the Nobelpharma implant system. Nobelpharma News 1987; 1:7.
55. Shigley JE, Mischke CR. Standard handbook of machine design. 1st Ed. New York: McGraw-Hill, 1986:23–26.
56. Sakaguchi RL, Borgersen SE. Nonlinear contacting analysis of preload in dental implant screws. Int J Oral Maxillofac Implants 1995; 10:295–302.
57. Dixon DL, Breeding LC, Sadler JP, McKay M. Comparison of screw loosening, rotation, and deflection among three implant designs. J Prosthet Dent 1995; 74:270–278.
58. Breeding LC, Dixon DL, Nelson EW, Tietge JD. Torque required to loosen single-tooth implant abutment screws before and after simulated function. Int J Prosthodont 1993; 6:435–439.
59. Bakaeen LG, Winkler S, Neff PA. The effect of implant diameter, restoration design, and occlusal table variations on screw loosening of posterior single-tooth implant restorations. J Oral Implantol 2001; 27:63–72.
60. Pameijer JH, Glickman I, Roeber FW. Intraoral occlusal telemetry. Part II: registration of tooth contacts in chewing and swallowing. J Prosthet Dent 1968; 19:151–159.
61. Junge D, Rosenberg JR, Halliday DM. Physiological tremor in human jaw-muscle system. Arch Oral Biol 1998; 43:45–54.
62. Abuyoussef H, Weiner S, Ehrenberg D. Effect of an antirotation resistance form on screw loosening for single implant-supported crowns. J Prosthet Dent 2000; 83: 450–455.
63. Binon PP. Implants and components: entering the new millennium. Int J Oral Maxillofac Implants 2000; 15:76–94.
64. Weinberg LA, Kruger B. Clinical utilization of nonrotational capability in osseointegrated prostheses: a technical note. Int J Oral Maxillofac Implants 1994; 9:326–332.
65. Hobkirk JA, Schwab J. Mandibular deformation in subjects with osseointegrated implants. Int J Oral Maxillofac Implants 1991; 6:319–328.
66. Beaty K. The role of screws in implant systems. Int J Oral Maxillofac Implants 1994; 9(Suppl):52–54.
67. Fenton AH, Zarb GA. Research status of prosthodontics procedures. Int J Prosthodont 1993; 6:137–144.
68. Gyllenram F. Handling and hard ware. Nobelpharma News 1994; 8:4–5.
69. White GE. Osseointegrated dental technology. London: Quintessence, 1993:82–83.
70. Binon PP. The effect of implant/abutment hexagonal misfit on screw joint stability. Int J Prosthodont 1996; 9:149–160.
71. Binon PP, McHugh MJ. The effect of eliminating implant/abutment rotational misfit on screw joint stability. Int J Prosthodont 1996; 9:511–519.
72. Khraisat A, Hashimoto A, Nomura S, Miyakawa O. The effect of lateral cyclic loading on abutment screw loosening of external hex implant system. J Prosthet Dent. (In press)
73. Binon PP. Evaluation of machining accuracy and consistency of selected implants, standard abutments and laboratory analogs. Int J Prosthodont 1995; 8:162–178.
74. Rangert B, Gunne J, Sullivan DY. Mechanical aspect of a Brånemark implant connected to natural tooth: an in vitro study. Int J Oral Maxillofac Implants 1991; 6:177–186.
75. Zarb GA, Schmitt A. The longitudinal clinical effectiveness of osseointegrated dental implants: the Toronto study. Part III: problems and complications encountered. J Prosthet Dent 1990; 64:185–194.
76. Quirynen M, Naert I, van Steenberghe D. Fixture design and overload influence marginal bone loss and fixture success in the Brånemark system. Clin Oral Implants Res 1992; 3:104–111.
77. Hoshaw SJ, Brunski JB, Cochran GV. Mechanical loading of Brånemark implants affects interfacial bone modeling and remodeling. Int J Oral Maxillofac Implants 1994; 9:345–360.
78. Johns RB, Jemt T, Heath MR, et al. A multicenter study of overdentures supported by Brånemark implants. Int J Oral Maxillofac Implants 1992; 7:513–522.
79. Rangert B, Sullivan RM, Jemt TM. Load factor control for implants in the posterior partially edentulous segment. Int J Oral Maxillofac Implants 1997; 12:360–370.
80. Daellenbach K, Hurly E, Brunski JB, Rangert B. Biomechanics of in-line vs. offset implants supporting a partial prosthesis. J Dent Res 1996; 75:183.
81. Parein AM, Eckert SE, Wollan BC, Keller EE. Implant reconstruction in the posterior mandible: a long-term retrospective study. J Prosthet Dent 1997; 78:34–42.
82. English CE. Biomechanical concerns with fixed partial dentures involving implants. Implant Dent 1993; 2:221–242.
83. Misch C, Bidez M. Implant protected occlusion: a biomechanical rationale. Compend Contin Educ Dent 1994; 5:1330–1343.
84. Weinberg LA. Reduction of implant loading with therapeutic biomechanics. Implant Dent 1998; 7:277–285.
85. Weinberg LA. The biomechanics of force distribution in implant-supported prostheses. Int J Oral Maxillofac Implants 1993; 8:19–31.
86. Weinberg LA. Reduction of implant loading using a modified centric occlusal anatomy. Int J Prosthodont 1988; 1:55–69.