Biomechanical Outcomes of Tooth-Implant-Supported Fixed Partial Prostheses (FPPs) in Periodontally Healthy Patients using Root Shape Dental Implants

SUMMARY

Background: Connecting an osseointegrated implant and a natural tooth is a treatment alternative for partially edentulous patients in some clinical situations. The main issue of a connected tooth-implant system is derived from the dissimilar mobility patterns of the osseointegrated fixtures and natural abutments causing potential biomechanical problems within the entire system. Purpose: The aim of this review was to multilaterally analyze and discuss the main biomechanical factors that may question the reliability of splinted tooth-implant system and the long-term success of fixed partial prostheses (FPPs) supported by both teeth and implants with an emphasis on the disparity of mobility of these two different abutments. Material and methods: An electronic MEDLINE (PubMed) search supplemented by manual searching was performed to retrieve relevant articles. An assessment of the identified studies was performed, the most valuable articles were selected and biomechanical outcomes of tooth-implant splinting system were analyzed. Results: 3D FEM stress analyses and photoelastic studies show uneven load distribution between the tooth and the implant and stress concentration in the crestal bone around the implant neck when connected to a natural tooth by FPPs. However, clinical studies demonstrate good results for both the implants and FPPs supported by splinted implant-to-tooth abutments. Conclusion: Connecting implants to natural teeth is not a preferable treatment option because of possible inherent biomechanical complications. Whenever possible, this treatment option should be avoided.

Keywords: Tooth-Implant Supported Prostheses, Natural Tooth, Osseointegrated Dental Implant, Occlusal Force, Finite Element Analysis, Rigid Connector, Non-Rigid Connector

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Introduction

The introduction of osseointegrated implants by Per-Ingvar Bränemark has had a revolutionary effect on all fields of dentistry¹. Dental implants were originally developed for the treatment of complete edentulism. However they are now widely used to treat partial edentulism, but the philosophy of this treatment concept, particularly regarding the connection of dental implants with natural teeth is still a big dilemma. The combined use of implants and teeth appeared in the mid 1980s². Numerous studies and analyses have been performed since then, but the conclusions derived from these studies differ considerably, and some of them are even contradictory. Several studies demonstrate a good prognosis for implant-tooth-supported FPPs²-⁸, others reveal considerable bone loss, even loss of osseointegration and failure of FPPs supported by natural teeth and endosseous implants.

There are several biomechanical factors that may jeopardize the entire prosthetic treatment and affect the long-term success of implant-tooth-supported FPPs such as: a) differences in the mobility pattern between natural teeth and osseointegrated implants, b) occlusal force pattern (that is the magnitude, duration, frequency, distribution and direction of the forces during the function), c) characteristics of prosthesis (rigidity,
connector type (rigid, non-rigid), connector position (near the tooth, near the implant), length of span, the features of materials of which the prosthesis is made etc.), d) characteristics of the implant system (implant shape, length, diameter, surface macrostructure, implant-to-abutment connection), e) characteristic of the bone around the teeth and the implants (the quantity and the quality of the bone), f) number of connected teeth and implants. All these factors determine the stress which affects the bone around splinted implants and teeth.

The main issue regarding splinting implants with natural teeth is the difference of their mobility pattern which could be considered as a biomechanical challenge for the entire splinted system.

Natural teeth with a sound periodontal ligament have a mobility between 15-20µm (axial displacement) and 150-200µm (horizontal displacement), while osseointegrated implants rigidly attached to the bone have a mobility of less than 10µm, which is due to a combination of the bone elasticity and the flexibility of the implant system (implant-prosthesis, implant-abutment, prosthesis flexibility itself). Such a discrepancy between the mobility patterns causes lever arm overload forces on the stiffer abutment (implant) and may lead to several physiological, mechanical and biomechanical problems (bone loss around the implants, abutment and prosthesis screw loosening and fracture, prosthesis and implant fracture, tooth intrusion) when implants are rigidly connected to teeth.

To overcome the difference in mobility and the above-mentioned problems in non-rigid connector types have been proposed by different authors. However, there is no clear consensus regarding the effectiveness of this type of connectors because of the potential clinical hazard of natural tooth intrusion. Several studies reported no significant difference between rigid and non-rigid connector types.

The position of the non-rigid connector in FPP is also an issue of discussion. It has been shown that placement of the non-rigid connector on the implant side rather than the tooth side of FPPs has both biomechanical and technical advantages. It was also documented that the use of the patrix part of the non-rigid connector on the implant site and the matrix part on the pontic site may be biomechanically efficient by reducing the potential harmful cantilever forces and stress formation around the implant.

Lawrence et al. advocated modifying the design of the conventional prosthesis (placing the attachment near one of the abutments (tooth or implant)) and to extend the cantilevers from both sides of the abutments and join them with an internal attachment at the middle part of the prosthesis. They insist that using this design will create less torque and stress on the implants without overloading the natural teeth.

Rangert et al. showed that a single Bränemark implant has an inherent bending flexibility that matches the axial mobility of a connected tooth. They advocate that a tooth rigidly connected to a single Bränemark implant will take an active part in supporting the axially applied forces of the prosthesis due to the resiliency of the implant screw joint and a momentary opening of the abutment-implant interface without any additional flexible element.

Chapman and Kirsch recommend the use of an intra-mobile element (IME) which would increase the implant abutment compatibility with natural abutments. This would therefore allow rigid interconnection through the prosthesis. The question of whether additional implant-integrated resilient elements are necessary is still controversial.

The second issue is the difference of tactile sensitivity threshold between implants and teeth which is 8.75 times higher for implants. This significant difference in mechanoperception may cause ineffective bite force control and stress concentration on the implant side of implant-tooth-supported FPPs.

Other studies affirm that the load condition is the main factor affecting stress distribution in different components of implant-tooth-supported FPPs (bone, prosthesis, fixture). Indeed, occlusal load duration, magnitude, distribution, frequency and the direction of the forces during the function have a great influence on both the FPPs and the abutments. Decreasing occlusal loading forces on the pontic area of the FPPs and directing these forces through the long axis of abutments significantly decrease the risk of unfavorable stresses within the prosthesis and the bone around the teeth and the implants.

Data concerning the number of splinted teeth and implants are also controversial. In their retrospective multicenter study, Lindh et al. found out that intrusion of natural teeth (which is one of the main complications when connected with implants) was most common in the prosthesis design with one implant connected to one tooth. Splinted natural teeth have less mobility compared with the mobility of a single tooth, thus making the whole unit mobility more comparable to that of the implants. The other hand, some authors insist that the addition of an extra tooth increases the load on the implants rather than supports them.

Splinting more than one implant will increase their resistance against occlusal loading forces and reduce the deflection of the prosthesis, thus reducing the risk of mechanical complications. Load transfer to implants and natural tooth changing the number of splinted implants were estimated by Nishimura et al. They performed quasi-3D testing, analyzed a photoelastic model and changed the number of splinted implants by removing of the abutment of the medial standing implant. The results showed higher apical stress concentration around the abutments when only one implant was splinted with a tooth regardless of the type of the connector. When forces were directed on the implant segment, the stress...
concentration around the tooth and the implant were similar to that of a two-implant condition. However, they concluded that a 13-mm implant as a posterior abutment may adequately support the 3-unit prosthesis rigidly connected to a tooth. Jemt et al performed a long-term follow-up study using Bränemark implants. They connected several implants to natural teeth and came to the conclusion that 2-3 implants (at least) are adequate to take the full load of the segment by themselves when splinted with natural teeth (the continuous prosthetic stability rate was 98.7%).

The aim of this study was to summarize the results of the existent stress analysis studies (3D FEA and photoelastic methods) and clinical studies to discuss the biomechanical outcomes of implant-tooth-supported FPPs with an emphasis on the differences between tooth and implant mobility patterns.

Material and Methods

An electronic MEDLINE (PubMed) search between 1980 and 2015 was conducted to retrieve relevant articles. A further manual search from the bibliographies of the former articles was performed to include as many references as possible. The search included English-language articles published in the Dental Literature.

The search terms used were: “tooth-implant connection”, “splinting”, “implant connected to a natural tooth”, “tooth intrusion”, “rigid connector”, “biomechanics”, “load distribution”, “tooth-implant-supported fixed partial prosthesis” and combinations of these terms.


From a total of 1879 titles electronically identified from the initial search, 95 studies were selected for potential inclusion (included by titles and abstracts). 63 studies were selected for full text evaluation (32 studies were excluded: cross-sectional, case reports, old implant technology), from which only 51 studies met the inclusion criteria and final data extraction. Prospective and retrospective clinical studies, as well as randomized controlled clinical trials (RCT) were included in this paper. Inclusion criteria for clinical studies involved patients with periodontally healthy teeth, root shape osseointegrated dental implants and fixed partial prostheses supported by both teeth and implants.

Studies based on 3D finite element analysis and photoelastic stress analysis were also included as these methods are extremely useful and have become the main tools for numerically assessing stresses and deformations in peri-implant bone, the bone around natural teeth as well as within the prosthesis. Articles based on 2D FEA and photoelastic stress analysis methods were excluded because of their limitations and drawbacks (lack of information and accuracy). One of the included articles contained both 2D and 3D FEA methods. Only information from 3D FEA results was extracted.

Studies, included implant-tooth-supported FPPs in periodontally compromised patients were excluded. Case reports, publications based on patient records only, questionnaires or interviews were also excluded.

Results

It is known from literature that teeth have a certain physiologic mobility within their respective alveolar sockets. This physiological mobility is due to the presence of a periodontal ligament (PDL) between the tooth and the alveolar bone surrounding it. The PDL is composed of intercellular ground substance (matrix), fibers (collagen, oxytalan, elaunin), and cells with their neurovascular supply. Tooth mobility is a direct function of the mechanical properties of the periodontal protein matrix with its collagenous elements. Tooth movement (TM) when a horizontal force is applied to the crown may be divided into 3 phases: a) initial TM, b) intermediate TM, c) terminal TM.

The initial (desmodontal) TM is explained by the special syndesmotic anchorage of the tooth in the alveolar bone. Within this phase the resistance of the tooth against the force is very small. This phase corresponds with a first phase of readiness orientation and stretching of the PDL fibers without strain. The collagen fibers of PDL have a wavy configuration in the relaxed state which enables the tooth to move easily without any resistance at the beginning of force application. This initial displacement of a natural abutment would cause stress concentration around a rigidly connected implant abutment before the two become comparable in their resiliencies.

The degree of desmodontal TM depends on several factors: the width of the PDL, the shape of the root, the structure, disposition and interlacing of the collagen fibers.

If the force is increased, the resistance of the tooth against that force will suddenly increase-in this state, the TM is at the limit between its initial and intermediate phase. In order to push the crown over a distance similar to the phase of initial TM, greater forces are needed (100-1500Gm). In this phase tooth movement occurs due to an elastic deformation of alveolar bone.

With an increase in force over 1500Gm pain is registered. During this phase the crown hardly moves anymore in spite of a strong increase in applied force.
(1500-1750Gm). Teeth with a healthy periodontium will show a narrow and sharply delimited zone of terminal TM. For several seconds the tooth will not yield any movement. Lasting stress produces further movement of the crown. A tooth with a sound PDL has horizontal and vertical mobility and the upper limit of physiologic horizontal tooth mobility is greater than that of vertical mobility (150-200µm vs 15-20µm)\textsuperscript{[3,4,9]}. PDL dampens the forces acting on a tooth. This damping effect is not only due to collagen fibers, but also due to the vascular system (blood and lymph vessels) and the interstitial fluid of PDL. Saul et al.\textsuperscript{[10]} performed an in vivo study on living and dead rats to find out the roles of different component parts of PDL in the reduction of the oscillation amplitude of a tooth in its socket, when the tooth has been subjected to intrusive force. They showed that the extracellular and the intracellular fluid systems have a hydraulic damping effect and dissipate the force acting on a tooth during an intrusion.

It can be concluded that due to the presence of the PDL the occlusal forces applied on the tooth are equally distributed on the bone around the root. The natural tooth receives the impact energy and transfers it to the end of the root in the form of a stress wave\textsuperscript{[11]}. Most of the energy is dissipated by the highly absorptive PDL.

An osseointegrated endosseous implant has a very close apposition to the bone. Besides, at the microscopic level there is a bone ingrowth to the macro- and micropores of the implant surface. Such a close contact allows for a direct transfer of stress from the implant to the surrounding bone without any relative movement between them and without any changes in magnitude or duration as the PDL and related mechanoreception is absent around an osseointegrated implant\textsuperscript{[22]}. An osseointegrated implant has only about 10µm displacement which is due to surrounding bone elasticity\textsuperscript{[12]}. Because of the lack of micromovement most of the force distribution is concentrated at the crest of the ridge\textsuperscript{[23]}. Lateral forces are concentrated at the crestal area of the alveolar ridge, vertical forces are concentrated at the crestal and apical parts of the bone\textsuperscript{[17]}. Because of the differences in the mobility pattern between teeth and implants, occlusal forces applied on the FPPs supported by both implants and natural teeth will be distributed on the bone differently compared with solely teeth-supported and solely implant-supported FPPs.

In solely teeth-supported FPPs situations the load is equally distributed between both abutment teeth when force is applied at the middle of the bridge. If the force is placed at the mesial or distal end of the FPPs the total load is carried by the mesial or distal abutment tooth, respectively\textsuperscript{[13]}. However, Lawrence et al.\textsuperscript{[17]} note that if occlusal force is applied only on one abutment it will evoke a micro-motion of the other abutment and the periodontal fibers will distribute generated compression, tension and rotational forces on all teeth.

In a free-standing implant-supported prosthesis, force application to one portion is distributed to the nearest osseointegrated fixture-bone interface. The force is concentrated at that interface and the amount of its distribution to the remaining implant(s) depends on the flexibility of the surrounding bone, implant, abutment, retaining screws and prosthesis. The amount of deformation of the retaining screws (most flexible part of the system) are in the range of 100µm. Therefore, the amount of force distribution to the remaining fixtures is much less than that found in natural teeth-supported FPPs (PDL can permit 500µm of movement)\textsuperscript{[17]}. However, the maximum load on each implant will be less than the applied complete occlusal force\textsuperscript{[27]}. In the case of the prosthesis supported by an implant and a tooth, the latter does not carry a fair share of loading as the resilience of the tooth is higher than that of the implant. When the force is applied at the tooth side and/or in the middle part (pontic) of the FPPs, the tooth dips into its alveolar socket causing bending of the prosthesis. This creates a bending moment on the implant neck-bone interface, which means that only one part of the force is carried by the tooth while the other (main) part is transmitted through the implant into the bone. The magnitude of this bending moment is dependent on the tooth mobility and the flexibility of the prosthesis, the implant and the bone\textsuperscript{[4]}. On the other hand, forces directly applied on the implant do not load the tooth and consequently, only the implant carries the complete load\textsuperscript{[13]}. Landgren & Laurell\textsuperscript{[14]} reported theoretical calculations and showed that an implant-tooth-supported bridge functions as a cantilever only for a very short time. At the beginning of load application the FPPs is supported by the implant only. After the moment is increased to a certain level (240Nm), the implant-abutment-crown unit rapidly angles in the lateral direction with a certain amplitude. They assumed that this deflection is sufficient for a tooth with a normal apical mobility to reach the bottom of the socket, and when intruded further, the apical yield of the root is close to zero (as of an implant), even if large forces are applied. If plus the bending of the beam, only 5-6N are needed to convert the bridge from an implant-supported cantilever construction to a bilateral construction (as the tooth touches the bottom of the socket, it doesn’t move apically anymore and starts sharing the forces with an implant).

The presence of the PDL provides not only physiologic tooth mobility, but also tactile sensitivity which plays an important role in the coordination of masticator muscle activity and control of applied occlusal forces. No periodontal ligament receptors are available for tactile function if the tooth is replaced by an endosseous implant\textsuperscript{[22]}. When the threshold of perception of teeth and implants are compared, higher values have been reported for implants. Hämmérle et al.\textsuperscript{[23]} conducted an \textit{in vivo} study to determine the threshold of tactile perception of
endosseous dental implants and to compare it with that of natural teeth. Twenty-two healthy subjects with implants of the ITI Dental Implant System were included in the study. A total of 34 implants were placed and served as abutments for single tooth crowns (in function for a minimum of 1 year). An electronic measuring device was used to determine the threshold values. The range of forces applied for calibration reached from 0.01N to 10N (1-1000g, 1g represents 0.01N force). The obtained values ranged from 13.2 to 189.4g (mean value of 100.6g) for the implants and from 1.2 to 26.2g for the control teeth (mean value of 11.3g). The mean threshold value for implants was 8.75 times higher than that for teeth. Thus, when a tooth with exquisite mechanoreception is connected to an implant with less mechanoreceptive sensitivity by FPPs, the magnitude of bite forces may increase when a patient bites on the implant side of the prosthesis. However, several studies have proved that the magnitude of bite forces in patients with osseointegrated implants is comparable to that of patients with natural teeth. Gunne et al. in vivo measured vertical forces for implants is comparable to that of patients with osseointegrated implants. However, several studies have proved that the magnitude of bite forces in patients with osseointegrated implants is comparable to that of patients with natural teeth. Gunne et al. in vivo measured vertical forces for implants and bending moments on 10 three-unit prostheses in the posterior mandible of 5 patients (intra-individual measurement). All patients had a prosthesis supported by one implant and one tooth in the molar region on one side (rigid connection) and a freestanding, two-implant-supported prosthesis on the other. The prostheses had been worn for 5-6 years. The results showed no significant differences in functional load magnitudes related to the abutment type. Akca et al. performed a similar study (in vivo) to evaluate maximal occlusal bite forces (MOFs) and marginal bone level changes in patients with tooth-implant-supported FPPs. They came to the conclusion that even MOFs under functional loading were higher for implants (mean: 353.61N) than for teeth (mean: 275.48N). These increased functional loads are far below an overloading of implants. In the same study, radiographic measurements revealed a stable marginal bone level around the implants and a total marginal bone level improvement from the baseline to 24 months at the mesial site (mean: 0.28 ± 0.519mm) and at the distal site (mean: 0.097 ± 0.518mm), which shows that this splinted system has a promising marginal bone level stability for the implants.

Several 3D finite element analyses have been implemented to assess load distribution and stress concentration in TISP. Lin et al. analyzed the biomechanics in a tooth-implant splinted system using 3D FEA with different occlusal forces for various bone qualities. They constructed a model which contained one Frialit-2 implant splinted to the mandibular second premolar that was embedded in a simplified bony segment. Four bone quality categories were established, with the elastic parameters assigned to the bone values varying. The stress distribution in the splinting system was observed under four different loading conditions. The results showed that lateral forces significantly increased the stress values of implants, prostheses and the alveolar bone compared with axial occlusal forces, regardless of the bone quality. Maximum von Mises stress values in the implant system (σI,max) and prosthesis (σP,max) demonstrated no significant differences between the bone qualities under the same loading condition, but the maximal stress values for the alveolar bone (σAB,max) increased when the bone quality was reduced. The authors of the aforementioned study also showed that decreasing the occlusal forces on the pontic area significantly decreased the values of σI,max, σP,max and σAB,max. Under axial forces the maximum stress concentrated locations in the implant system were found at the contact butt-joint interface between the abutment and the implant, the bottom of the internal hexagon joint of the abutment and threads of the abutment screws. Under the same forces the maximum stress concentrated locations of σAB,max and σP,max were found at distal cervical areas in the cortical bone and bottom of the mesial connector, respectively. For the lateral loading condition the corresponding locations of σI,max, σP,max and σAB,max were found at the contact butt-joint of the implant, lingual cervical areas in the cortical bone and the lingual bonded region between the prosthesis and the abutments, respectively.

In another study Lin et al. tried to investigate the biomechanical interactions in TISP by varying the number of splinted teeth and connector types. They constructed a 3D FEA FPPs model which contained one Frialit-2 implant in the mandibular second molar region splinted to the first and second premolars. They came to the conclusion that load condition was the main factor affecting the stress developed in the implant, bone and prostheses when comparing it with the connector type and the number of splinted teeth. The 3D FEA showed reduced stress values in centric and lateral contact situations when the occlusal forces were decreased on the pontic (26-69%). Under uniform multiple oblique forces the σI,max were at the base of the internal hexagon joint of the abutment and mesial butt-joint interface between the abutment and the implant. The σAB,max were concentrated on the lingual cervical areas in the cortical bone around the teeth and the implant side when the occlusal forces acted only on the premolar and on the prosthesis, respectively. Regarding the connector type they came to the conclusion that using non-rigid connector increased the prosthesis stress more than 3.4-fold compared with the rigid connector. Depending on the specific connector used, the σP,max were on the concave surface of the male component and bottom area for non-rigid and rigid connectors, respectively. Regarding the number of splinted teeth they found that this factor did not affect stress values either for the implant or for the alveolar bone or for the prosthesis.
Menicucci et al. implemented 2D and 3D FEAs to assess the stress in the bone around an implant and a tooth which are rigidly connected when a load is applied to the tooth. Two different loading conditions were compared in this study: an axially directed static load (10 seconds) and a transitional load (5 milliseconds). The results of the 3D FEA showed the stress concentration at the neck of both the tooth and the implant when static load was applied. Under short term transitional forces the stress around both abutments was much less (-50%) than that seen under the static loading. Thereby, they concluded that load duration has a greater influence on the amount of generated stresses in the bone around the implant rigidly connected to the tooth than load intensity, and that the static loads are more detrimental for the bone than the transitional loads. They suggested that the main reason for these results were the visco-elastic properties of the PDL and the very short load time which is removed before the loaded tooth starts to sink in its alveoli (before visco-elastic creep occurs). As a result the tooth reacts like a rigidly anchored abutment sharing the load with the implant.

Nishimura et al. conducted photoelastic stress analysis to evaluate stress distribution in an implant-tooth splinted system using different types of connectors. They fabricated a life-size photoelastic model of an adult human mandible for quasi-3 dimensional testing. The edentulous area was extended distally from the second premolar. Two screw-type implants (3,75mm diameter, 13mm length) were included into the model at the first and second molars. Multiple restorations incorporating 3 types of connections between the medial implant and the natural tooth were fabricated: a) non-connection (proximal contact only), b) rigid solder joint, c) non-rigid connection. Vertical point loads were applied at 6 fixed identified locations on the occlusal surface of the tooth-implant restoration: T, over natural tooth, 1- medial to implants, 2-over medial implant, 3-inter-implant, 4- over distal implant, 5- distal to implants. The results of the non-connected model were as follows: loading directed on the tooth (point T) transferred low stress to the apices of both implants (the distal implant received a smaller amount of forces compared with the medial implant), the highest stress intensity was seen apical to the natural tooth. Loadings directed on the implant areas (loading points 1-5) produced little or no discernible stress in the apical areas of the tooth; the later was concentrated to the distal parts close to the implants. Thus, when the load was applied over each abutment, the highest stress intensity was seen apical to that abutment. The highest stress within the structure was produced under loading on point 5. The distal implant underwent intrusion and distal bending. Stress was concentrated at the distal crest and at the apex of that implant.

Results of the non-rigid connection between the abutments were similar to those of the non-connected situation. When the abutment of the medial implant was removed, a 3-unit fixed restoration was simulated with a pontic. In this type of model, when force was applied at the load point T, stresses concentrated at the apical part of the implant were twice as high as the 2-implant condition. The highest stresses were observed at the second implant with the load applied at points 4 and 5. Low level stresses were produced within the distal part of the tooth because of its distal bending ability.

In the rigid connection scenario the results showed the following: for the 2-implant model, when the load was applied on the tooth abutment, similar apical stresses were generated around the tooth and the medial implant. Some low level responses were noted at the distal surface of the medial implant and at the medial surface of the distal standing implant. As the forces were directed to the implant segment, stresses also transferred to the distal part of the splinted system. The highest stresses were observed around the distal implant along its distal surface and at the apex when the load was applied at point 5 (which indicates the intrusion and distal bending of the implant).

Several in vivo studies have been performed by different authors to investigate the biomechanics of IMZ. Richter et al. presented data from their in vivo study in which 10 tooth-implant-supported FPPs in the mandible of 9 different patients were examined while the intra-mobile elements (IME) of 3 IMZ implants were replaced by a measuring device with strain gauges. After the abutment screws were fixed, the measuring device was calibrated. The results showed higher buccal than lingual directed stresses (only in 6 of 34 registrations). Measured lateral bending moments were up to 25N×cm during occlusion and chewing.

Another in vivo study was performed by Gunne and Rangert. They measured in vivo bite forces, implant axial forces and bending moments on 5 patients with FPPs supported by a natural tooth and a single Brånemark implant rigidly connected to each other by a MacCollum attachment and a locking screw. The patients were divided into two groups according to the magnitude of the applied forces, a light-biting group and a hard-biting group. The results demonstrated mean forces of 12N and 95N for light-biting and hard-biting groups, respectively. They also showed that in the light-biting group the tooth did not fully engage and the implant carried the major portion of the applied bite force. For the hard-biting group, the tooth shared the load on an equal basis with the implant. They reported bending moments of 3-5N×cm and 10-16N×cm for the light- and hard-biting groups, respectively.

As mentioned earlier the type of connector used is also an important biomechanical factor affecting stress distribution in the tooth-implant system. Several authors advocate the use of a rigid connection, which assumes a stiff junction between component parts of the structure with no relative motion of one part against another. The use of this type of connector reduces tooth intrusion incidence and transfers the load.
more evenly through the prosthesis, but as the tooth and the implant have a different degree of mobility, more stress is concentrated around the implant which has been shown by the aforementioned as well as other FEA and photoelastic studies. To overcome the disparity in mobility of the different abutments, non-rigid connectors have been introduced. Indeed, a flexible prosthesis will tend to redistribute the load between the abutments with unequal stiffness. With a flexible bridge the tendency for any applied load is to be primarily transmitted to the nearest abutment whether it is a natural tooth or an implant. In this situation the exact point of applied occlusal force becomes a priority. The use of a non-rigid connector may be more efficient in terms of compensation for the dissimilar mobility under axial loading forces only. However, under lateral occlusal forces this compensation becomes insignificant. It should be mentioned that most of tooth intrusion cases in splinted systems were detected when non-rigid connectors were used. Hence, a potential priority of one type of connector over another is still unclear.

To increase the compatibility of implants with teeth IMZ implants (Interpore-IMZ, Irvine, Calif.) were introduced with an intra-mobile element between the implant and the prosthesis. Richter et al. used IMZ implants in vivo and in vitro study to measure the bending moments on the implant caused by axial and lateral forces. They fastened four different types of connecting devices: 1. IME, 2. an intra-mobile connector (IMC), 3. a titanium metal IME and 4. a mobile test device. The results were as following: the max bending moment was 40% of the highest stress using a metal IME (640 Nmm), 25% with the IME (400 Nmm), 15% with the IMC (240 Nmm) and 14% for the test device (224 Nmm).

Van Rossen et al. estimated the effectiveness of stress-absorbing elements and their role in stress-absorption and stress-distribution in the cortical and trabecular bone around a tooth and an implant when connected to each other. In their FEA they proved that using a stress-absorbing element with a low E-modulus both damps and distributes the loading forces more uniformly in the bone surrounding the implant and the tooth. We can summarize that resilient elements improve the load distribution between two different abutments by decreasing implant stiffness, thus, making the interconnection more compatible. Moreover, these shock-absorbing elements allow a rigid, yet retrievable connection between teeth and implants. It should be mentioned, however, that this design of implant-prosthesis connection has drawbacks, such as wear, fatigue and/or fracture, which requires a frequent replacement of the resilient component.

Bone characteristics (quality and quantity) are one of the most important issues to consider when planning an implant-tooth treatment. It has been proved that stress in the bone surrounding the implant increases with reduced bone quality. The maximum stress concentrations were found in type IV bone (Lekholm and Zarb classification, 1985) followed by type III, II and I. In a type I bone, the stress distribution is more uniform as the entire bone block is compact and homogeneous. The results from studies confirm that implants connected to teeth should be used with caution in softer (type IV) bone regions.

3D FEA is generally accepted as a very useful tool to assess stress generation and mechanical responses of simulated clinical situations. However, the constructed FE models are mathematical models of the real object and/or phenomenon. Hence, it is not possible to reproduce all the details of the real loading conditions, material properties and the geometries of the component parts especially the geometry of the alveolar bone, and some important parameters that influence the clinical outcomes of implant-tooth-supported FPPs may be overlooked. Such a parameter is the limitation of calculation of the host reaction to the stresses applied. Therefore the results derived from FEA only provide a general understanding of the biomechanical aspects of the splinting system and need to be completed and validated by clinical studies.

Several clinical studies and systematic reviews have been implemented to find out the survival rates of implants and FPPs supported by implants and natural teeth.

Mau et al. have compared two different coatings of intra-mobile cylinder implants (IMZ, Koch 1976) - hydroxyapatite (HA) and titanium plasma-flame (TPF) – between patients with Kennedy Class I or II mandibular partially edentulous arches in a randomized controlled trial and estimated the cumulative success rates of the implants after 5 years of follow-up period. All FPPs were supported by one natural tooth (first or second premolar) and one implant placed in the molar region. The connection between the implants and the teeth was rigid (screw-retained attachments). From all 313 admitted patients 155 (49.5%) were randomized to HA-coated IMZ implants as test group and 158 (50.5%) patients were randomized to TPF-coated IMZ implants as control group. The main criteria of comparison were the duration of no integration deficiency (ID) and of no functional deficiency (FD) of the implants after the placement of FPPs (the authors defined ‘integration deficiency’ as implant loss, bone loss since the operation of at least 4 mm at the medial or distal aspect, periosteal value of at least 10, manual mobility grade >0). The 5-year cumulative success rates for no ID were 69.5% (95% CI, 58.3-80.7%) with HA and 82.2% (95% CI, 74.2-90.6%) with TPF.

Naert et al. conducted a retrospective study to evaluate the success of the freestanding and tooth-implant connected FPPs up to 15 years of follow-up period. A total of 668 Bränemark implants were placed in 246 patients. In 123 patients, 339 implants were connected to 313 teeth by means of FPPs (test group). In another randomly selected group of 123 patients, 329 implants were connected to
This study is limited by a small number of patients. The implants and the marginal bone stability. However, detected. Therefore, they concluded that splinting teeth components (fracture, loosening) or superstructure was no implant failed and no mechanical failures of implant 14 years of follow-up time the results were ‘excellent’ supported by 48 implants (Bränemark system). After 14 years of follow-up time the results were ‘excellent’: no implant failed and no mechanical failures of implant components (fracture, loosening) or superstructure was detected. Therefore, they concluded that splinting teeth with implants does not affect the long-term outcomes of the implants and the marginal bone stability. However, this study is limited by a small number of patients.

Gunne et al.7 compared the outcomes of the FPPs supported by implants only with FPPs supported by splinted implants and teeth. 23 patients with Kennedy Class I dentitions in the mandible were included in the study. All patients were provided with implants ad modum Bränemark on each side posterior to the mandibular residual teeth. On one side the FPPs were supported by two implants, and on the other side the FPPs were supported by one tooth and one implant. A total of 69 implants were inserted and 46 FPPs were fabricated and followed-up up to 3 years. The authors showed interesting results about fixture survival, FPPs survival and marginal bone loss when comparing solely implant-supported and implant-tooth-supported combination bridges. The survival rate of the implants was 88.4% and for both types of FPPs it was the same. The survival rate of the FPPs was higher in implant-tooth combinations than in solely implant-supported FPPs (91.3% vs 82.6%). They also observed lower mean marginal bone loss adjacent to the implants connected to the natural teeth than those that were adjacent to the non-splinted implants.

Pjetursson and Lang performed a 2-part meta-analysis to find out the survival rates of implants and FPPs after an observation period of 5 and 10 years for free-standing implant-supported and implant-tooth-supported FPPs. After 5 years of observation, the survival rates for implants were 95.4% (95% CI: 93.9-96.5%) and 90.1% (95%CI: 82.4-94.5%) in free-standing and implant-tooth-supported situations, respectively. After 10 years of observation the survival rates were 92.8% (95% CI: 90-94.8%) and 82.1% (95% CI: 55.8-93.6%), respectively. After 5 years of function the survival rates for FPPs in free-standing and implant-tooth-supported cases were 96.6% (95% CI: 95.9-97.3%) and 94.1% (95%CI: 90.2-96.5%), respectively. After 10 years of function the survival rates for FPPs were 90.4% (95% CI: 79.8-95.6%) and 77.8% (95% CI: 66.4-85.7%), respectively. As it may be seen from the results, the survival rates for both implants and FPPs were lower for splinted implant-tooth-supported cases compared with solely implant-supported situations. Annual failure rates of implants in combined implant-tooth-supported FPPs (1.33%) were significantly higher than those of implants in free-standing implant-supported FPPs (0.51%).

Discussion

There are some clinical situations in which an implant-tooth connection is unavoidable and the only choice of treatment such as: a) an insufficient number of natural teeth or implants (when insertion of additional implants is not possible because of systematic, local or financial limitations) to serve as sole abutments for FPP, b) additional support for periodontally compromised teeth from stable implants, c) unfavorable location and distribution of abutments (both teeth and implants), d) prosthetic versatility and retrievability. Splinting implants with natural teeth also has several advantages: proprioception from natural teeth, broadened treatment possibilities, better esthetic outcomes (retaining the natural tooth preserves the adjacent papillae), reduced treatment cost, additional support for total load on dentition etc. However, decision-making criteria for rehabilitation of partially edentulous arches by splinting implants with natural teeth are still a dilemma. Clinical studies (both prospective and retrospective) show good prognosis for combined implant-tooth-supported FPPs. Lindh et al.5 conducted a retrospective multicenter study which comprised 185 implants in 111 patients from 6 different clinics in Sweden. The results showed a cumulative implant survival rate of 95.4% for up to 3 years of follow-up. The frequent complications were loss of osseointegration (6/185), followed by peri-implant infections (4/185) and natural tooth intrusion (15% of the cases). Another retrospective study conducted by Hans et al.6 evaluated clinical treatment outcomes of FPPs using different sizes and numbers of teeth and implants as abutments (follow-up up to 8 years). They presented a cumulative implant survival rate of 89.8% after 5 years of service. Jemt et al.8 performed another retrospective study on 876 consecutively placed implants (Bränemark system) in a total of 244 patients treated and annually followed at the Bränemark clinic (Gothenburg, Sweden) for up to 20 years. The authors aimed to find out the results of the treatment of partially edentulousness by means of FPPs supported by osseointegrated implants. From 876 implants 43 were connected to the adjacent teeth to support 12 FPPs in total of 9 patients. The authors did not observe any significant problems associated with the connection.
of implants with teeth. However, they mentioned that treatment involving a mechanical connection between teeth and implants should be approached with caution.

Although these and many other studies show successful treatment outcomes, two main complications associated with splinting an implant with a natural tooth, which are bone loss around the implant and natural tooth intrusion, still question this treatment option. Tooth intrusion is one of the main problems when connected to implants which can occur in up to 7.3% of the cases\(^{29}\). Several studies tried to explain the causes of this phenomenon\(^{31,47}\), but till now there is no clear answer. Some authors insist that the cause of intrusion is multifactorial\(^{31,48,49}\). Some of the possible factors are: disuse atrophy, differential energy dissipation, impaired rebound memory, rachet effect, debris impaction, fixed prosthesis flexure, mandibular flexure (only in mandible). It has been shown to occur mainly in teeth non-rigidly connected to implants\(^{4,6,38}\). However, this problem can also occur with any other attachment type\(^{37,48}\). Several authors showed a reversibility of tooth intrusion\(^{31,50}\) by disconnecting solder joints or other methods (occlusal adjustment, changing the contours of coping sidewalls etc.).

Studies involving 3D FEA and photoelastic analyses, in vivo and in vitro, prospective and retrospective studies were included in this study. Differences in mobility and tactile sensitivity of natural teeth and osseointegrated implants were discussed, the main biomechanical factors affecting the longevity and success rate of combined FPPs have been introduced, the survival rates of implants and FPPs supported by solely implants and splinted implant-tooth abutments were compared in the current paper. Both short- and long-term clinical studies, retrospective and prospective studies and systematic reviews show acceptable results for implants and FPPs. However stress analysis methods (3D FEM and photoelastic) show more stress concentration around the implants and within the superstructure.

The current paper contains certain restrictions, as the other important biomechanical factors, such as implant characteristics (length, diameter, surface macrostructure), the proximity of the splinted teeth and implants to each other, material of prosthesis (type of alloy for metal framework, veneering material - acrylic, ceramic), opposing construction type in antagonist jaw (fixed, partial or complete removable dentures) were not included and discussed.

**Conclusion**

There are several clinical situations in which a tooth-to-implant connection seems to be the only treatment option. However, planning this construction type the practitioner should realize the potential biomechanical problems that may jeopardize the longevity and successfulness of the complete treatment. Natural teeth have a physiologic mobility due to the PDL, which is absent in osseointegrated dental implants. Hence, connecting these two different abutments causes uneven load distribution between them, and as a result possible implant abutment overloading.

A decision should be based on well-considered treatment planning, i.e. choosing periodontally healthy teeth, planning the positions and number of inserted implants, directing occlusal forces through the long axis of abutments and performing a meticulous management of the occlusion.

As we can see from the available studies there is no definite opinion neither about the number of splinted implants and teeth, nor about the connector type, position and rigidity. Only one thing is clear: when connecting implants with teeth, the implants will always carry the greater part of the loading.

To give a definite answer to: “Is splinting an osseointegrated implant with a natural tooth a reliable treatment option?” further research and long-term studies are needed.

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**References**


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