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Biomechanical Behaviour of Tooth-supported Fixed Partial Dentures by 3d Fea

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Abstract - *This three-dimensional finite element analysis first described stresses distribution in loaded posterior fixed partial dentures, then compared the influences of bone height, abutment roots number and pontic length on their displacements. Twelve mandibular (three to five unit) FDPs integrating periodontal ligaments were designed. Stresses were localized in connectors and cervical areas of abutments near the edentulous span. The main FDPs' displacements consisted of vertical translation increasing with low bone height. FDPs underwent simultaneously an antero-posterior displacement (about ten times smaller) towards the weakest abutment side. Splinted abutments affected this anteroposterior displacement. Span length was associated with small beam deflection.*

KEY WORDS: Fixed partial dentures. Dental abutments. Finite element analyses. Biomechanics. Alveolar bone loss.

INTRODUCTION

The placement of conventional tooth-supported fixed partial dentures (FDPs) induces a rigid connection between dental abutments, which were subject to physiological movements[1]. Moreover, these abutment teeth support missing tooth loads that result in additional mechanical strains. In this context, numerous prosthodontics guide books state on FDPs behaviours and designs by referring to "biomechanics rules", even if they are often inspired by mechanical principles or clinical experience.

Span length is considered as a critical strains generator, associated with main FDP displacements[2]. After comparing a loaded FDP to a simple beam (submitted to 3 points bending), it has been stated that pontic's deflection at mid-length could increase with the cubed length, according to $d= (F.l^3)/(4E.b.h^3)$ (d: mid-length deflection, F: applied force, l: beam length, E: Young modulus, h: beam height, b: beam width). Furthermore, the balance of root anchorage seems a crucial condition for providing FDP's stability. Ante's law suggests that the root surface area of abutment teeth (embedded in bone) should be at least equivalent to the theoretical root surface area of the replaced teeth[3] (Fig.1a). Practitioners may therefore wish to have splinting of multiple abutments to overcome mechanical problems[4] created by a long edentulous span or the loss of bone support of an abutment. It has yet been suggested that these splinted retainers could unseat, due to bordering abutments acting as fulcrums[2] (Fig.2). Moreover, low bone heights induce important lever arms[5-7], and a minimal 1:1 ratio of clinical root/crown has been proposed[2] for considering teeth as FDPs' abutments (Fig.1b).

A three-dimensional finite element analysis (3D FEA) is a computer-based method used to calculate and visually represent stresses and displacements in complex structures subjected to simulated loads. The calculations require knowledge of the materials' mechanical properties, such as Young's modulus (E) and Poisson's ratio (ν). This numerical stress analysis technique is widely used today to study biomechanical problems in prosthodontics[8-11].

This study aimed to describe stresses distribution and displacements of a loaded posterior FDP, and to compare the influence of different parameters that define the behaviour of these associated structures, such as bone height, abutment roots number and pontic length.

MATERIALS AND METHODS

The software package used in this study was CADSAP (CADLM, France), French version of SUPERSAP (ALGOR® Interactive Systems, USA). A 3D modelling assuming linear elasticity was carried out. The material data (Young's modulus, E; and Poisson's ratio, ν) used in the calculations are presented in Table 1.

In our study, tooth-supported FDPs designs were evaluated in a case of an interrupted mandibular arch. The second premolar and/or the first molar were lost. The abutment teeth were single-rooted premolars and multi-rooted molars (Fig.3) surrounded by a 0.35 mm periodontal ligament (PDL)[12]. Teeth were in the centre of a bony structure and connected by a nickel-chrome (28% and 22% respectively, Mesa, Italia) FDP. General rules were applied for the preparation of natural teeth and creation of metallic restorations[2]. Between the cemented parts, zinc phosphate thickness was assumed to be standardized (50μm[13]). The bridge was subject to a vertical load set at 10N[14], and applied at pontic's mid-length on the occlusal surface centre. Since this study was comparative, intensity and direction of strength applied to the occlusal surface did not affect the outcome. The bony structure was considered as fixed laterally and apically. The assumptions made in this study are explained in the discussion section.

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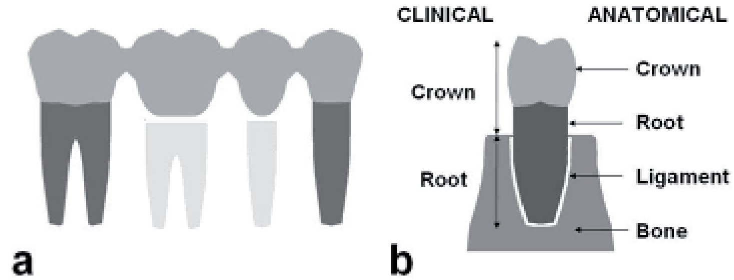

Figure 1. Current guidelines of FDPs designs.
a- Facial view of a mandibular four-unit FDP replacing a molar and a premolar. Root surface area of abutment teeth should be at least equal to the theoretical missing root surface area,
b- Proximal view of a mandibular premolar. A minimal 1:1 ratio of clinical root/crown is needed for FDPs abutments.

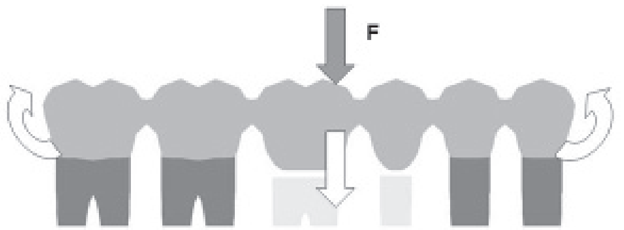

Figure 2. Splinted retainers unseat under pontic loading.
Facial view of a mandibular six-unit FDP replacing a molar and a premolar. Under loading, splinted retainers could unseat, with bordering abutments acting as fulcrums (grey arrow: force applied, white arrows: movements).

Table 1. *Materials' Elasticity Modulus (E, Young's modulus in GPa) and Poisson Proportions (ν, Poisson's ratio), as previously described[42-44].*

Materials	*E (GPa)*	*Poisson's ratio*
Dentin	18	0,31
Cancellous bone	1,37	0,30
Periodontal ligament	0,08	0,45
Zinc phosphate cement	22	0,35
Ni-Cr alloy	203	0,3

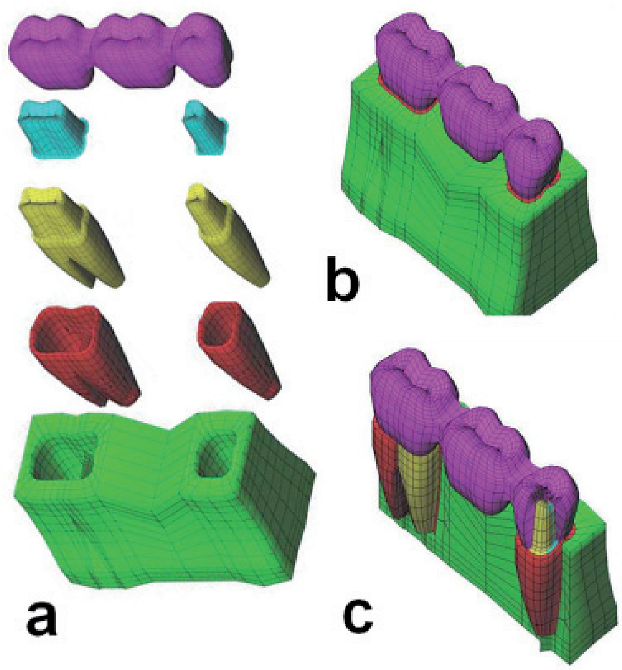

Figure 3. Realistic 3D structures for FDP models.
a- Structures modelled for a three-unit FDP (green: bone, red: PDL, yellow: prepared teeth, blue: cement, purple: FDP),
b- Assembled structures.
c- Selective section of the assembled structures.

Twelve models (Fig.4) were compared. The FDPs replaced a premolar and/or a molar, and abutment teeth number varied on both side of the pontic (3 to 5 unit FDP). These situations were analyzed under 3 different bone heights, corresponding to the half, the two thirds or the full anatomic root length.

The dental displacements and the stress distribution within abutment teeth and surrounding bone were calculated. Focus was on von Mises equivalent stresses, as it makes the study comparable with related publications. These shearing stresses are the common mode of illustration for areas where plastic strains are potentially taking place. The stress distribution was represented as iso areas showing mean stresses in Pa. Red and orange indicated high-intensity stresses, purple and blue indicated low-intensity stresses. Anteroposterior and vertical displacements were measured at the top of facial cuspids bordering edentulous span (mesial one for molars). The beam deflection (occluso-apical displacement of the pontic) was calculated from the global displacements at mid pontic minus the mean displacement of the cuspids bordering the edentulous span.

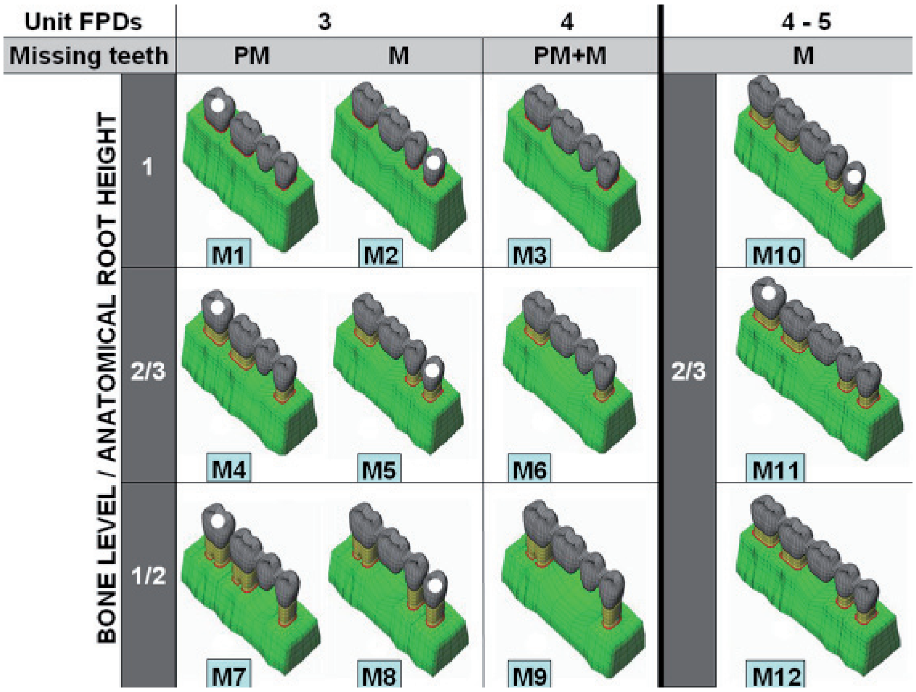

Figure 4. Twelve FDP models were compared.
Models had different bone heights, span lengths and numbers of abutments (PM: premolar, M: molar, white point: tooth disconnected from the FDP).

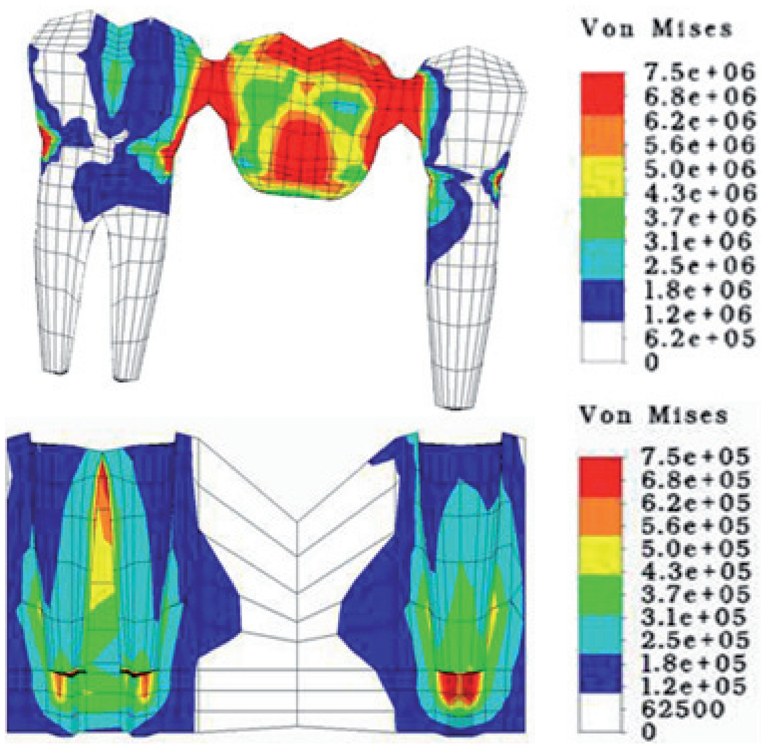

Figure 5. Stress distribution in FDPs and in the surrounding bone: *representative example of M5. Von Misses stresses are displayed in color categories of iso-stress value. Warm colors (red, orange, yellow) represent highest stress values and cold colors (green, blue) lowest values.*

RESULTS

Stresses distribution

Stresses distributions were similar on the different FDP models (Fig.5). Stresses in splinted abutments were about ten times smaller than those in primary abutments.

Some Von Mises stresses appeared occlusally on the pontic, where the force was applied. Stresses were mostly localized in the connectors (between pontics and bordering abutment teeth), and the highest stresses were observed on the weakest abutment side. Dentin cervical areas of the teeth bordering the edentulous span were solicited, especially on the distal side. Stresses decreased progressively all along the dental roots facing the edentulous span. Cervical stresses of abutment teeth increased with the abutment roots imbalance.

The observation of cancellous bone showed various stresses intensities. The greatest stresses appeared first in the apical region of the premolar alveolus, then in the apical region of the molar alveolus and finally in the molar roots furcation. Stresses were then progressively distributed along the alveolar wall from the apical area to the cervical area. The cervical area of the weakest abutment bordering the edentulous span was slightly more solicited than the others.

Displacements

Once loaded, the analyzed structures underwent displacements. Regardless of the considered model, an axial load resulted in driving vertically the whole structure into the supporting bone. Then a anteroposterior displacement of the structure towards the weakest abutment side was observed (Fig.6a). Splinted abutments followed this general displacement (when comparing M5 and M10-12).

The occluso-apical translation intensity depended mainly on the height of bone tissue (when comparing models M1-9, Fig.6b). The mean drive-in of the whole structure increased with low bone height (respectively by 20% for 2/3 bone height and 60% for ½ bone height). Vertical translation amplitude was reduced by approximately 37% when splinting an abutment to the original 3-unit FDP, and by 86% when splinting one on both sides (Fig.6b). Span length was only a secondary factor regarding vertical displacement increase. The amplitude of anteroposterior displacements was approximately ten times smaller (fig.6c), and depended mostly on abutments imbalance. The addition of a molar abutment to the 3-unit FDP led to a 67% increase of anteroposterior displacement towards the premolar (when comparing M5 to M10, Fig.6c), while the addition of a supplementary premolar abutment (M12) led to a 41% decrease of this displacement towards the premolar. Increasing abutment roots number on the premolar side only led to a small anteroposterior displacement towards the molar (when comparing M5 to M11), which has become the weakest abutment side. Edentulous span length and bone height were only secondary factors for anteroposterior displacement increase.

Regardless of the models, beams deflection was characterized by very small amplitudes (Fig.6c). Deflection of short pontics (premolar or molar) ranged from 0.25 to 0.35µm and increased with span lenght (1.35-1.70µm for premolar and molar). Deflection increased secondarily with the number of abutment teeth.

DISCUSSION

The aim of this study was first to examine stress distribution, and then to compare the influence of different parameters (pontic length, abutment roots number and bone height) on FDPs displacements. The main purpose was to compare the biomechanical behaviour of the FDPs rather than report absolute values for displacements and stresses.

As models can easily be accommodated to hypothesis, FEA has proved to be an accurate and convenient tool for evaluating the mechanical behaviour of prosthodontics layouts[8-10]. The program used in this investigation has several limitations considering the unrealistic simulation of the structure's material properties. This static study assumes that the bone, the tooth, and the PDL are homogeneous, linear-elastic and isotropic. It does not take into account materials fatigue due to the repeated loads and the complexity of masticatory forces.

When a load is applied, the occlusal force gives rise to stresses and to strains (resulting in displacements) within the associated structures. FEA and in vitro studies on FDP's mechanical behaviour often use a load applied on the pontic[5,15,16]. This load type corresponds to special situations, such as chewing of a rigid aliment between the pontic and the antagonist tooth. However, stress distribution is quite similar when the load is distributed on all the working cusps, but with smaller intensities [17]. Although the load investigated lacked the complexity of the loading which occurs in the oral environment, the findings are of value when comparing the alternative designs of FDP investigated. The magnitude and direction of applied forces influence the resulting stress distribution [18]. This study however did not focus on critical FDPs displacements associated with maximal bite forces, but on single tooth loads during mastication, which spread between 3 to 18 N[14]. The masticatory system has the capability to produce bite force over a large range of directions. Our applied force only had an axial component as lateral ones make the results complex without particular interest for this displacements analysis. In literature, PDL thickness ranges in width from 0.15 to 0.38 mm, with its thinnest portion around the middle third of the root, showing a progressive decrease in thickness with age[12]. A low bite force and a large PDL (0.35 mm) were chosen to underline the influence of the PDL on displacements. Despite its viscoelastic and anisotropic properties, the PDL was treated as a linear elastic isotropic medium. This assumption is not so important when a static load is applied without time study.

Cement and PDL thickness were assumed to be standardized. Layer variations would have been time consuming and of low interest in this displacement comparative study. Between the sealed parts, the cement thickness was assumed to be 50 µm[13]. The use of different luting agents with different elastic moduli has, however, a minor effect on the resulting stresses in FEA. The effect of different thicknesses of these luting agents is even smaller[19].

However, in reality, the mastication forces and the tooth/bone interface are dynamic. It is consequently impossible to reproduce all the details of natural behaviour. FEA can not determine criteria for acceptability of stress levels, but enables to compare different models and to quantify the risk in each of them. Dental morphology is strongly related to the functions carried out by teeth, more work will be needed to match reality.

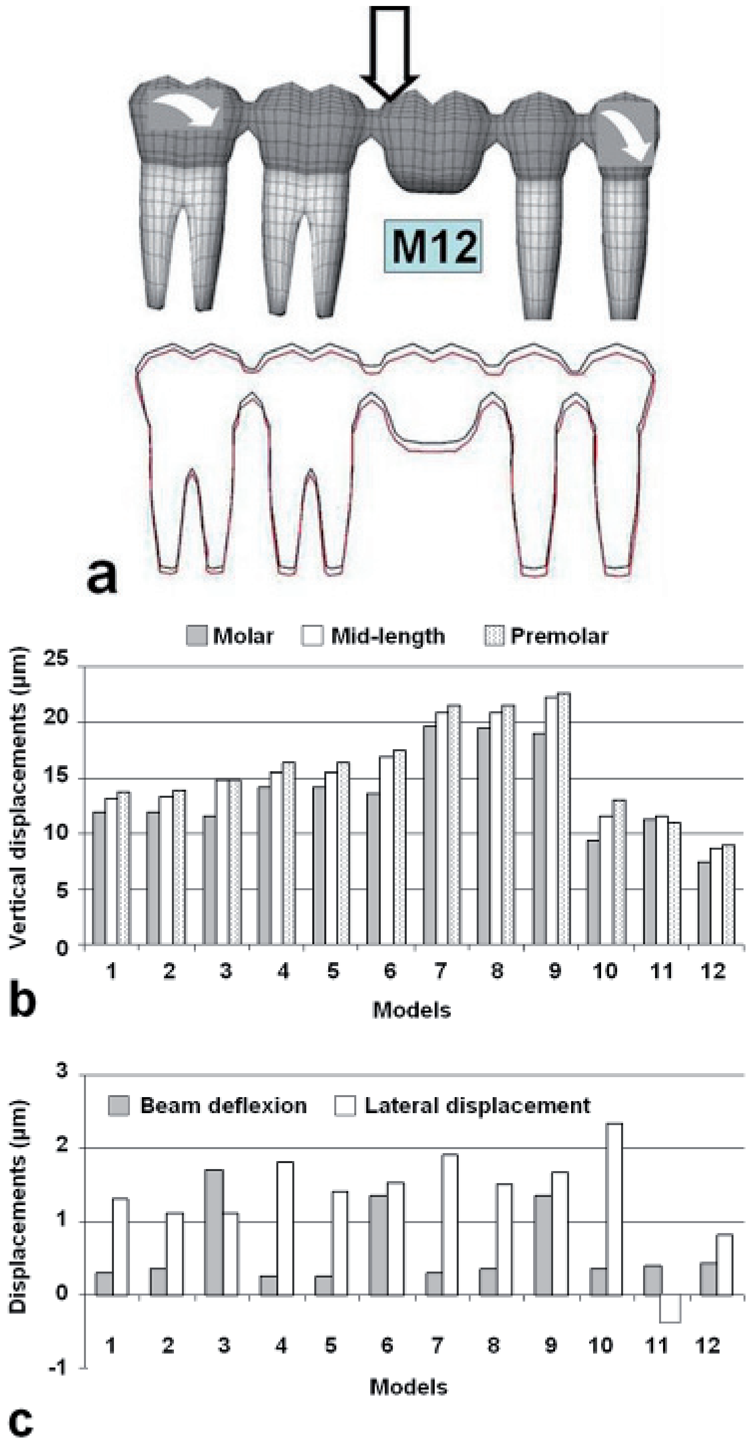

Figure 6. FDPs displacements under loading.
a- Magnified FDPs displacements (M12 for example): under loading, the FDP described a vertical translation associated with a anteroposterior one towards the weakest abutment side.
b- Vertical displacements of molar and premolar bordering the edentulous span, and at beam mid-length. The vertical translation, calculated on each occlusal tooth centre, depended on the bone height (M1-M9), and was reduced when splinting an abutment (M5, M10-12).
c- Anteroposterior displacements and beam deflection. Anteroposterior displacements, calculated on each occlusal tooth centre, were approximately ten times smaller than vertical ones, and depended mostly on the abutments imbalance. Beam deflection was increased by long pontics (premolar plus molar).

Stresses were mostly localized in the connectors between pontics and abutments, and in the cervical and apical regions of the tooth. This distribution is consistent with FEA and in vitro studies on FDP's mechanical behaviour [5,15,16]. These regions are considered as the weakest points of the prosthesis with the greatest potential of fractures, regardless of the material used[20, 21]. In FEA literature, most of FDP's studies aim to determine precise levels of stresses in cantilevers[16, 22], resin-bonded[23, 24], all-ceramic connectors[17, 20, 21, 25, 26] or implant-supported[27-29] FDPs. Very few investigated displacements of conventional FDPs. Manda et al. recently investigated by 3D FEA the effect of severely reduced bone support (50 and 30% of anatomical root length) on cantilever FDPs[22]. They concluded that alveolar bone loss did not affect the pattern of stress distribution in the connectors linking the splinted teeth, but resulted in changes in its extent. These finding suggests that connectors should be bulky to ensure optimum strength and the prosthetic materials employed should have high yield strength and rigidity.

Under simulated occlusal loading conditions, the main FDP displacement consisted in a vertical translation (occluso-apical direction), equivalent to an impaction of the structure into the subjacent bone tissue. This phenomenon is consistent with a previous 2D FEA by Yang et al.[4] on various 4 to 6 unit FDPs. Simultaneously, the structures underwent anteroposterior displacement towards the weakest abutment side. Yang et al. described only a mesial displacement, decreasing gradually with splinted abutments, because they did not try to multiply abutments on the premolar side only.

This phenomenon is mainly due to the integration into our analysis of PDL. Indeed, the PDL suspends the tooth in the alveolar bone and plays a crucial role in dental mobility[30,31]. Its width varies considerably with age and tooth while its texture is modified by functional stress[32]. The ligament has been found to be thinner around hypofunctional teeth and hypertrophic around overloaded teeth. A proliferation and thickening of its constitutive fibres appear when functional overload is maintained durably. In our models, this sheath surrounding bone-embedded abutments, more elastic than the bone tissue[33], is useful in a first approximation. Visco-elasticity phenomena are not taken into account, but these simplifying approximations do not necessarily denature problems if taking care of abusive extrapolations.

In our study, the height of bone tissue surrounding abutments determines the amplitude of vertical movements. The impact of reduced bone height has been previously described by FEA with identical results [4, 22]. Clinically, the influence of bone level has been a matter of some controversy. Some studies showed an increased risk for failure in situations where alveolar bone level was reduced [5-7]. In contrast, other studies reported good long-term results in the same clinical conditions[34-37]. Mechanically, the extra-alveolar lever arm seems to increase when the amount of root embedded in bone tissue decreases, concurrently increasing the occurrence of harmful lateral forces. However, FDP prognosis depends more on the quality of periodontal support than its quantity[35, 38] as ensuring good health and long-term maintenance can preserve FDP abutments with severe bone loss.

Increasing the number of abutments did not lead to a proportional reduction of abutments displacements but compensated only partially the mechanical incidence of a long-span pontic. Connecting splinted abutments on either side of the pontic presents a mechanical advantage only if this leads to balancing the structure. The vertical translation amplitude decreased by connecting splinted abutments, except when it led to imbalance abutment values. These results are consistent with previous FEA study[4]. The "Ante's law" [3] is useful as a clinical guideline, even if it does not guarantee clinical success[39]. Tang and Chen[40, 41] showed also that mechanical stresses recorded in premolars are twice those found in molars. Additionally, splinted abutments underwent no specific stresses and followed the FDPs global movement. This point is at odds with previous mechanical theory[2], which suggests that splinted abutments unseat by rising.

The relative deflection of the beam mainly depended on beam length though its amplitude was very small. This point is in opposition with the mechanistic explanation[2] suggesting that beam's deflection at mid-length could increase with the cubed length. Our results suggest that PDL leads to a biomechanical behaviour more than a strict mechanical one.

This study illustrates one of the many applications of finite element analysis. On the condition of several approximations, this method integrates some biomechanical parameters in the associated structure analyses and dramatically changes the understanding of the specific problems posed by fixed partial dentures. Bone loss is the most critical determinant of posterior FDPs mobility, and requires great health for favourable prognosis.

CONCLUSIONS

This study showed that the FDP behaviours in its biological environment – featuring abutments, PDL and supporting bone tissue - is fundamentally different from a beam. Within the limitations of this 3D FEA, the following conclusions can be drawn:

- Stresses were mostly localized in the connectors and in the cervical area of abutments near the edentulous ridge.
- The main FDPs' displacements consisted in a vertical translation, whose amplitude increased mostly with low bone height.
- FDPs underwent simultaneously a anteroposterior displacement, about ten times smaller, towards the weakest abutment side.
- Splinted abutments could increase anteroposterior displacement by creating an imbalance in root numbers.
- Span length is associated with small beam deflection.

Regarding abutments stresses, when teeth on either side of edentulous span are not altered, the implant-based solution is an alternative to consider.

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