Tooth displacement due to occlusal contacts: a three-dimensional finite element study

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SUMMARY The use of the Finite Element Method (FE) is an appropriate way to study occlusal forces and tooth movement. The purpose of this study was to evaluate the effects of different occlusal contact patterns on tooth displacement in an adult dentition using a three-dimensional FE model of a human maxilla and mandible. Initially, images of a computerized tomography scan were redrawn in a computer program (CATIA) followed by the FE mesh construction. The MSC/Patran software was used to develop the FE mesh comprising 520 445 elements and 106 633 nodes. The MSC/Nastran program was utilized as pre and post-processor for all mathematical calculations necessary to evaluate dental and mandibular biomechanics. Four occlusal patterns were tested: FEM 1 – standard occlusal contacts; FEM 2 – removal of mesial marginal and mesial tripoidism contacts; FEM 3 – removal of distal marginal and distal tripoidism contacts; FEM 4 – similar to FEM 3 with added contacts between upper and lower incisors. Small changes in the standard distribution of occlusal contacts resulted in an imbalance of occlusal forces and changes in dental positioning. All simulations tested showed mesial displacement of posterior teeth. The most significant changes were registered in the model presenting unstable occlusal contacts when the anterior teeth were in occlusion (FEM 4). These findings may explain mandibular incisors crowding and maxillary incisors flaring as a result of small variations in dental contacts.

KEYWORDS: tooth displacement, occlusal equilibrium, biomechanics, finite element method

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Introduction

Occlusal contacts in humans occur on inclined planes and have a great influence on maintaining tooth position and mandibular stability. When the occlusal system balance is disturbed some negative effects may take place (1). For example, muscular alterations, parafunctional habits, dental mobility, occlusal trauma, tooth migration and mandibular incisor crowding might occur (2). This last clinical condition is sometimes attributed to late mandibular growth, rebound of interdental fibres or even to unerupted or erupting third molars (3, 4).

Several methodologies and study models have been developed to evaluate the masticatory system dynamics. Initially, rudimentary physical models such as dry human skulls were used (5). Transparent photo-elastic resin models and pure mathematical models were also applied (6, 7).

The FE method has been implemented in order to study the stomatognathic system dynamics (8, 9). It has shown promising results for analysing the intensity, frequency, duration and direction of occlusal forces, as well as their influence on the stability of tooth positioning (10, 11). A remarkable advantage of this method is the chance to study areas that are difficult or
impossible to access without any risks to a human sample (8, 12).

The use of FE allows studying a single tooth, a set of teeth, or even the relationship between maxillary and mandibular dental arches on a more solid and precise biomechanical basis than other methods such as photo-elastic models and strain gauges (13). Therefore, with this methodology it is possible to have quantitative and qualitative representations of dental and mandibular biomechanics to evaluate tensions, deformations and displacements that may occur in these structures (13–15). The more defined the model, the more precise the FE analysis (16, 17).

Despite the recent advances in the measuring tools described above and the increasing number of publications evaluating the influence of occlusion on tooth displacement, a relevant clinical question is still not fully explained: are the tooth displacements noticed with aging somehow related to changes in the occlusal contacts? Thus, the purpose of this study was to evaluate the effects of different occlusal contact patterns on tooth displacement in an adult dentition using a three-dimensional finite element model of a human maxilla and mandible.

Materials and methods

The construction of the three-dimensional FE model was initiated with 2 mm sections of a multiplanar computerized tomography (CT) scan\(^*\) of a young adult with complete permanent dentition, except for the third molars. The research protocol of this study was approved by the Ethics Research Committee of the Pontifical Catholic University of Minas Gerais, Brazil.

One hundred and ninety-five two-dimensional CT scan images were stacked with computer design software\(^†\) in order to accurately develop the three-dimensional model. During the development of this model, mandible, maxilla and teeth were built independently and considered as independent parts with uniform mechanical properties. While the mandible was drawn replicating its complete anatomical structure, the maxillary graphic reproduction was performed without taking the maxillary sinus into consideration because its anatomical variations would significantly increase the drawings complexity. In addition, the maxilla was drawn up to an upper horizontal limit formed by a plane passing through the anterior nasal spine and the external acoustic meatus on both sides.

After all bony structures were graphically represented each of the 28 teeth was drawn separately with no differentiation concerning enamel, dentine or pulp and considered as an independent part. Despite the relevance of the periodontal ligament (PDL) (18) when occlusal forces are taken into consideration, it was not considered an independent anatomical structure during the elaboration of this model. This decision was because of the significant difficulties in mechanically modelling the PDL. These difficulties come from the existence of very different length scales of its biomechanical properties and to the complexity in reproducing its reduced dimension in a FE model (19). Thus, the construction of a PDL FE model would require a significantly smaller mesh to obtain congruent meshes between teeth and bone, demanding remarkably more complex mathematical calculations without necessarily generating more precise data for this type of experiment (19).

The final three-dimensional graphic models generated by the CATIA programme were transferred to the MSC/Patran software\(^‡\) using Parasolid format files. This software adopted the self-adapting criterion to build superficial and internal structure meshes using tetrahedral elements with three degrees of freedom per node. At the end of this process, the FE model presented a mesh comprising of 520,445 elements and 106,633 nodes.

Following the model construction, the mechanical properties of the anatomical structures tested and their response to all different occlusal simulations were performed with the MSC/Nastran software\(^‡\). The results of these calculations were transferred back to the MSC/Patran software to obtain their graphic representations.

The mechanical properties of the dentin were assumed as being the whole tooth, using a 21,400 MPa elastic modulus and a 0.31 Poisson coefficient, as previously described by Grenoble et al. (20). In addition, a 0.30 Poisson coefficient and 14,500 MPa elastic modulus characteristic of cancellous bone were considered for the whole bone structure (21). This simplification was performed because the goal of this preliminary study was to evaluate exclusively tooth displacements separate from possible tensions and

\(^*\)Picker, model PQ2000; Highlands Heights, OH, USA.

\(^†\)CATIA – Dassault Technologies, Woodland Hills, CA, USA.

\(^‡\)MSC Software Corporation, Santa Ana, CA, USA.
deformations that may affect the independent parts tested.

The horizontal plane previously described acted as the upper limit of the model, presenting rigid restrictions that inhibited displacements beyond that area (Fig. 1). The clinical simulations tested did not require total freedom for mandibular movements in the area representing the temporomandibular joint (TMJ). Therefore, elastic restrictions with a rigidity coefficient of $1 \times 10^{-7}$ N m$^{-1}$ were implemented in this region to permit small mandibular positional changes.

The FEM constructed for this experiment used a mathematical resource known as transition element (or interface element) (19) to transfer the displacements from one tooth to its adjacent and antagonist in the inter-proximal and occlusal areas respectively. The Patran software named this numerical tool Multi-Point Constraint (MPC). The MPC transition elements do not add any elastic properties to the bodies involved. Therefore, they did not increase the rigidity of the structures evaluated and behave only as transfer elements.

Four loading situations were created to simulate the following hypothetical occlusal conditions by selectively adding or removing MPCs which corresponded to different occlusal contacts (Fig. 2): FEM 1 – standard closure occlusal contacts (canines and posterior teeth in occlusion) with balanced distribution of complete cusp-fossae and cusp-marginal crest contacts, as previously reported (2); FEM 2 – occlusal contacts similar to FEM 1, except for the removal of the distal contacts. There were no tooth contacts between upper and lower incisors in FEM 1, 2, and 3. FEM 4 was similar to FEM 3, except for the addition of occlusal contacts between upper and lower incisors. All occlusal contacts described above were created by establishing MPCs between maxillary and mandibular teeth. The various occlusal schemes tested were obtained by selective removal or addition of different MPCs.

The three-dimensional FEMs were submitted to static occlusal load tests to simulate the action of the muscles responsible for the mandibular elevation: masseter, temporal and lateral pterygoid muscles based in previous publications (14, 15). These forces were applied at the FEM nodes representing the areas of anatomical insertion of these muscles and the force vectors followed the muscle fibers path (Fig. 3). The forces comprised a total of 490.5 N, which has been described as a heavy physiological masticatory force (22).

**Results**

The FEM 1 data showed that all teeth presented mesial displacement tendencies. However, mandibular teeth presented higher displacement degrees than the maxillary arch as the reference; FEM 3 – similar to FEM 2, except for the removal of the distal contacts. There were no tooth contacts between upper and lower incisors in FEM 1, 2, and 3. FEM 4 was similar to FEM 3, except for the addition of occlusal contacts between upper and lower incisors. All occlusal contacts described above were created by establishing MPCs between maxillary and mandibular teeth. The various occlusal schemes tested were obtained by selective removal or addition of different MPCs.

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**Results**

The FEM 1 data showed that all teeth presented mesial displacement tendencies. However, mandibular teeth presented higher displacement degrees than the maxillary arch. The highest mean values of total tooth movement were found in the second lower molars, progressively decreasing towards the canines and increasing again on lateral and central incisors. The vertical (Z-axis) displacements presented posteriorly decreasing values. Conversely, antero-posterior (Y-axis) displacements demonstrated that all teeth presented highest mean values anteriorly. Such findings could indicate tendencies for mesial tooth displacement, especially the incisors, which showed the greatest values. The lowest tooth displacement results were observed laterally (X-axis).

The mean displacement values in all three directions tested were greater in FEM 2 than in FEM 1. Mandib-
ular teeth displacements were greater than those observed in the maxilla, especially along the Z-axis. An important finding when applying this model was the smaller resultant force vector registered at the maxillary incisor edges in FEM 2 when compared with FEM 1.

The occlusal contacts in FEM 3 showed mesially oriented resultant forces for upper teeth and distally oriented for the lowers. The displacements showed a distribution pattern 120% larger than in the previous models. The Y-axis displacements were larger for all teeth, especially for the maxillary incisors.

FEM 4 data showed the largest degrees of displacements among all simulations tested. Despite having significant lower incisor displacements, the results were even more remarkable when analysing the behaviour of the upper incisors antero-posteriorly (Y-axis), as seen in Figs 4 and 5.

Discussion

The application of FE models enables the study of human body areas that are difficult to access, simulating important clinical situations without any risks to a human sample (10, 13, 23). The use of this research methodology to evaluate biomechanics has increased in recent years in all dental specialties. Studying the maxillary molar behaviour taking into consideration the occlusal contacts (11), evaluating the articular disk elastic properties (23) and measuring maxillary central incisor displacements after the application of a given orthodontic force (24) are examples of previous studies that have validated FE studies in Dentistry. Mathematical interface transfer elements are implemented to transmit displacements from one independent part to the other in non-linear FE analyses. The software used in the present article names its transfer elements Multi-Point Constraint (MPC). Although MPCs have been used in other areas, its validation in medical and dental FE analyses needs further investigation.

Although a detailed evaluation of tooth displacement because of different occlusal contacts is more realistic when all teeth are considered in a three-dimensional FE model, most studies reported to date have utilized either two-dimensional models (16, 17), or a three-dimensional simulation involving a limited number of teeth (11, 23, 24). The present study is one of the few to utilize three-dimensional FE analyses to evaluate the effects of occlusal changes when all maxillary and mandibular teeth are involved.
The FE model developed in this investigation had a mesh of 520,445 elements and 106,633 nodes with three degrees of freedom per node, what make this a significantly detailed model. Such characteristic is quite important to validate the results of FE studies since the more refined the mesh, the more accurate the model (11).

Fig. 4. Resultant teeth displacements in Y-axis (mm).

Fig. 5. Graphic representation registered at maxillary and mandibular central incisor edges.
The FE model construction protocol used in this investigation followed the methodology reported in previous studies (15, 16). When using such guidelines some simplifications are required to permit the construction of the models, to decrease the mesh complexity, and consequently to allow for a more objective computerized analysis. The simplification was basically considering mandible, maxilla and teeth as isotropic materials. Such procedure do not diminish the precision of the data generated by these models (13, 16, 21, 25).

All different loadings were performed with a static load of 490·5 N representing a heavy physiological masticatory force (22). The only variable changed in this study was the point of force application by altering the occlusal contacts. Since these modifications simulated small clinical changes, the results may demonstrate the relevance of occlusal equilibrium on tooth position stability. In addition, the graphic representation of tooth displacements in all three planes of space presented in this study help to elucidate the effects of the resultant vectors caused by changing the dental contacts.

FEM 1 simulated an equilibrated occlusion with adequate posterior contacts and no anterior teeth contacts, what has been reported as an ideal occlusion (2). The results of this simulation showed that even the best equilibrated occlusion presented a minimal anterior resultant force vector. Although there is no other detailed three dimensional FEM showing similar results, there have been clinical reports indicating the presence of such forces (1–4).

FEM 2, 3 and 4 represent progressively worsening of occlusal conditions. Their results showed that the more unstable the occlusal contacts the greater the tooth displacement found. FEM 4 was the only simulation presenting anterior teeth contact and its data showed the largest degrees of both upper and lower incisor displacements antero-posteriorly. These results are in accordance with other reports in the literature that recommends soft anterior teeth contacts while the posteriors are in occlusion (22). This result may provide an explanation why some patients tend to develop crowding of these teeth with aging.

Although the FEM loading was instantaneous, the results of this study clearly showed that small alterations in occlusal contacts commonly observed in prosthetic, orthodontic or restorative treatments could disrupt the balance of the occlusal system. Therefore, one could hypothesize that higher forces acting for longer periods of time would generate even greater tooth displacement, as observed in some malocclusions, parafunctional habits and severe periodontal disease because of alveolar bone loss (4, 22, 26).

The continuous development of FE models may generate more reliable data that could be applied to frequently seen clinical situations. Such improvements could be achieved by characterizing the PDL or by simulating changes in the alveolar bone and dental properties. These developments may facilitate the performance of dynamic tests with different mandibular movements, time dependent occlusal loads and with friction coefficients.

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