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CRANIOFACIAL SKELETON (TG CHU AND S AKINTOYE, SECTION EDITORS)

Orthodontic Tooth Movement Studied by Finite Element Analysis: an Update. What Can We Learn from These Simulations?

Paolo M. Cattaneo [1] · **Marie A. Cornelis** [1]

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Abstract

Purpose of Review To produce an updated overview of the use of finite element (FE) analysis for analyzing orthodontic tooth movement (OTM). Different levels of simulation complexity, including material properties and level of morphological representation of the alveolar complex, will be presented and evaluated, and the limitations will be discussed.

Recent Findings Complex formulations of the PDL have been proposed, which might be able to correctly predict the behavior of the PDL both when chewing forces and orthodontic forces are simulated in FE models. The recent findings do not corroborate the simplified view of the classical OTM theories.

Summary The use of complex and biologically coherent FE models can help understanding the mechanisms leading to OTM as well as predicting the risk of root resorption related to specific force systems and magnitudes.

Keywords Orthodontics · Finite element · Tooth movement · Periodontal ligament · 3D

Introduction

The prevalence of clinically meaningful malocclusion among adults in the USA has been reported to be more than 60% [1], with percentages varying according to the studied population and the criteria used [2, 3]. Orthodontic treatment is offered to patients to solve malocclusion in about 25% of the population in the Netherlands [4] and 25–33% of the children and adolescents in Denmark (source: The Danish Ministry of Health. Bekendtgørelse om tandpleje. Tandplejebekendtgørelsen: Lovtidende A; 2006). Orthodontics is a clinical intervention where load on the crown of the teeth is used as the therapeutic tool to move the teeth in the desired position to provide an optimal occlusion [5••]. Indeed, it is accepted that orthodontic tooth movement (OTM) is determined by a load-adaptive response of the alveolar support structures following the application of a force system on the crown of a tooth, involving all the processes of cellular mechanotransduction [6]. This also makes the study of OTM a perfect setup to study bone modeling and remodeling in a more general term, together with the possibility to study strain-adaptive–driven tissue remodeling in the periodontal ligament (PDL), and relate these results to the function of other joints in the body.

In the past, two main theories have been proposed to explain OTM (i.e., the "pressure-tension" theory [7, 8] and the "distortion or bending of the alveolar bone" theory [9, 10]); more recently both of them have been questioned by Melsen and Cattaneo et al. [11, 12] based on the hypothesis, already mentioned in 1965 by Frost and co-authors, that alveolar bone response to changed loading conditions cannot be different from the way bone adaptation is generally occurring in the rest of the skeleton [13, 14].

In an attempt to revise and clarify the mechanobiology of OTM, Henneman et al. [15] proposed a new theoretical model where, following the application of an orthodontic force, the changes in matrix strain, fluid flow, cell strain, and cell activation are explained and coupled. This model is able to explain OTM, providing a revised view of all the mechanical and biological processes related to tooth movement, in close resemblance and agreement to the mechanotransduction mechanism mentioned before.

A new theory, the *Biphasic Theory*, has been proposed aiming to describe OTM by addressing both the bone

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✉ Paolo M. Cattaneo
paolo.cattaneo@unimelb.edu.au

[1] Melbourne Dental School, Faculty of Medicine, Dentistry and Health Sciences, University of Melbourne, 720 Swanston St, Carlton VIC, Melbourne 3053, Australia

metabolism and the peculiarity of orthodontic forces to be fundamentally static in contraposition to the dynamic forces seen in the rest of the body; yet, this theory lacks elucidation of some aspects of OTM and, as such, does not present conclusive evidence [16].

The explanation of the alleged discrepancy between the orthodontic and the orthopedic world is the presence of the PDL between the teeth and the alveolar bone, which has been recognized and underlined in some of the publications studying OTM [17, 18••]: the presence of the PDL makes the load transfer from the crown of the teeth via their roots into the alveolar bone very different from what observed in the rest of the skeleton (e.g., in long bones). Indeed, the PDL can be characterized as a fibrous joint lying between the root(s) of a tooth and the surrounding alveolar bone, predominantly constituted by connective tissues (bundles of collagen fibers) and fluid [19, 20]. The PDL serves to attach the teeth to the alveolar bone; it plays a crucial role during mastication in distributing and damping the high masticatory forces, it is essential for tooth eruption, and, as mentioned before, it is allowing for OTM to happen [21, 22•, 23].

Another difference between OTM and the adaptive changes seen in long bones is the level of stress and strain seen when orthodontic forces (typically in the 10-200cN range) are applied at the crown level during orthodontic treatment. When such light forces are applied, the resulting strains in the alveolar bone have been calculated to be in the range of 5 to 100 micro-strains [17, 24–27], which, according to the windows proposed in the *mechanistic theory* of Frost, are far below the strain level necessary to trigger adaptive bone remodeling (i.e., modeling) [14, 28, 29].

Finally, orthodontic forces are typically administered by appliances that deliver almost constant and static forces, while, from the classic experiment of Lanyon and Rubin [30, 31], it is clear that only dynamic strains are able to induce a bone response.

Tensegrity and Tooth Movement

The concept of *tensegrity* (tensional integrity, or the physiological preexisting tensile stress in the cell) has been proposed to describe the way strain-mediated cellular activities are shaping and stabilizing living cells, and it can be extended to tissues and organs, up to the whole body. In other words, *tensegrity* governs how mechanical forces are determining form and function of cells inhabiting all living tissues [32]. This state of tension balance is kept by the interaction of the cell to its neighboring cells by external adhesions through integrins at the extracellular matrix (ECM) level and by other molecular filaments like microtubules that locally resist inward directed tensional forces inside the cytoskeleton. In the tissues, fibroblasts maintain a balance between the external tensile stresses that act on them via the ECM and the traction forces generated by their own cytoskeleton. By applying the concept of tensegrity to the dental field, it has been hypothesized that an altered *tensegrity* status in the alveolar support structures (e.g., generated during OTM or induced by periodontitis) would lead to immediate changes in cytoskeletal mechanics, leading to specific cellular responses and eventually to alveolar bone resorption or formation, or more specifically, that a “strain relaxation” signaling pathway would be the trigger to initiate OTM [33].

Finite Element Analysis and OTM

Among various analytical tools to study OTM, and more precisely to understand the load transfer from the crown to the alveolar support structures via the PDL and the subsequent adaptation of the alveolar socket, the finite element (FE) analysis is probably the method that has been applied the most: according to a search in Scopus (Elsevier), the FE analysis has been used in orthodontics all in all 994 times, with 601 articles published in the last 10 years (search string: “finite element” AND “orthodontic*”, search performed on September 30, 2020). Indeed, the FE method allows to quantify the state of loading in the periodontium in a nondestructive way, and it has been used in dental biomechanical research since 1973 [34]. In order to generate meaningful results, a FE model needs correct modeling of morphology, material properties, loading, and boundary conditions, which represent the major challenges for a proper biomechanical model [12, 35]. Certainly, the morphology of the alveolar support structures, comprising the PDL, bone, cementum, and entheses between the PDL and bone and PDL and cementum, is very complex [25]. In particular, the determination of the material property of the PDL is not trivial [18••, 36]. Yet, as underlined in a critical review of the literature [18••], a large discrepancy in the definition of the elastic constants and mechanical properties of the PDL exists, with variations “on the order of six orders of magnitude,” thus suggesting that research is necessary to fill this knowledge gap.

The geometry of FE models can be produced following different procedures: using anatomically correct models, anatomically simplified models, or geometrical models. It is important to underline that, whatever the procedure, FE models are only simplified representations of the actual structures they are attempting to depict: simplifications, both with respect to morphology and material properties, are introduced during modeling.

- Anatomically correct models are generated from 3D information of the periodontium of one single patient or specimen, which is typically obtained from computed tomography (CT), cone beam CT, or micro-tomography. The main advantage of using the first two methods is the availability of large databases; however, the voxel dimension of the dataset (typically in the range 0.2–0.5 mm) sets the limit to the quality and level of details that can be achieved using this technique. This is very relevant, especially considering that the thickness of the PDL is about 0.2 mm (Fig. 1) [37].

Conversely, micro-tomography, which is a well-established tool in the field of bone biomechanics, where it is typically applied to analyze the microstructure of compact and trabecular bone [38], is characterized by smaller voxel dimensions (higher resolution), thus achieving higher levels of details when compared to CT and CBCT datasets. The quality of the scan and the level of details of this noninvasive technique can be further enhanced using a monochromatic beam, instead of a traditional microradiographic technique, which makes use of a conventional X-ray source (Fig. 1) [25, 39, 40]. Based on this high-resolution approach, Dalstra et al. [40] were able to demonstrate that the alveolar bone surface is not smooth but that a number of irregularities and spikes as well as perforations are present at the PDL-alveolar bone interface. Hence, it was postulated that, due to this characteristic micro-architecture, even mild orthodontic forces can give rise to high local stress and strain in the alveolar support structures, as this structure seems to have great impact on the local level of strain: it has been reported that the microscopic strains can be up and over fifteen times greater than the applied macroscopic strain [41].

The main disadvantage of using anatomically correct models is the time-consuming and labor-intensive procedures necessary to generate and solve the FE model.

- In case of anatomically simplified models, averages of anatomical components or specimens (considered as representative of the average morphology) are used as input to build the geometry of the FE model. Following this approach, pathological/non-pathological variations, which might be present in anatomically correct models, are removed. This allows to generate results that can be more easily generalized.
- Last, geometrical models are generally built using mathematically described objects (e.g., paraboloid, cylinders, and cubes) to generate idealized shapes, which vaguely approximate the shape of the teeth and supporting structures. The main advantages of this approach are the relative easiness of model generation and interpretation of the results, together with the fact that material properties and morphology can easily be changed in a series of FE simulations. However, the results are generally difficult to

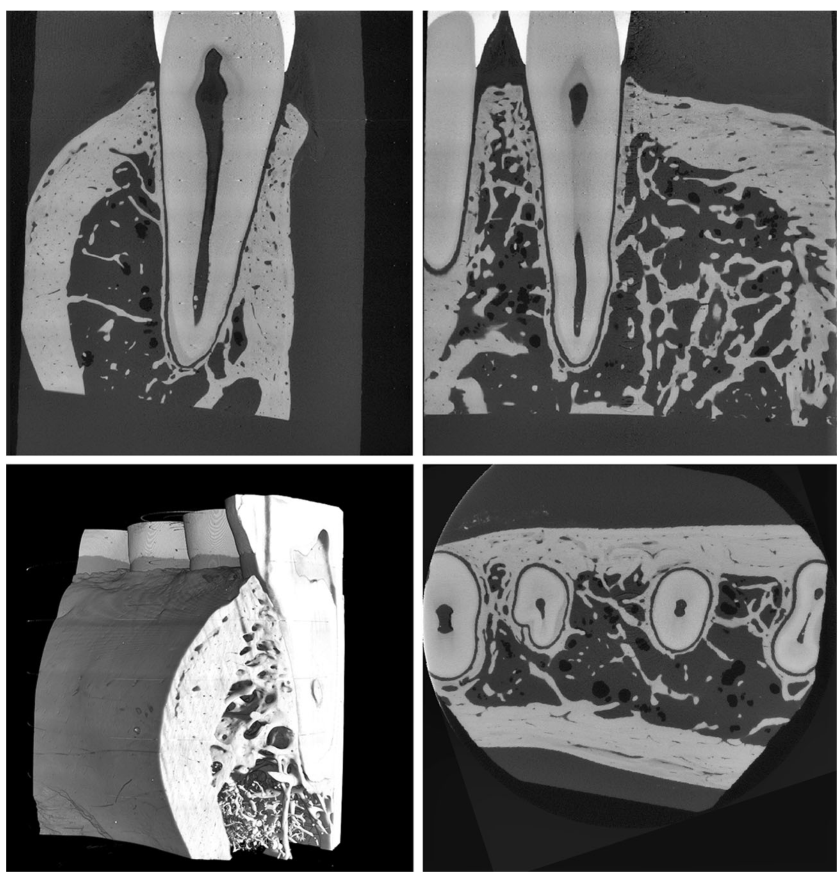

Fig. 1 Synchrotron radiation–based images of a mandibular alveolar bone sample (19-year-old donor obtained at autopsy, ethical approval #20010016, Aarhus Amt Ethical Committee, Denmark). It is worth noticing the high complexity of the trabecular structure, the inhomogeneous bone support, and the uneven shape of both the roots and the surrounding thin alveolar bone

apply to real teeth, given that the simplified geometry does not take into account the morphology of the actual teeth and alveolar bone.

The choices for determining the morphology of the teeth in FE models have been debated extensively. Indeed, geometry and dimension of the teeth and alveolar bone have been reported to have a significant impact on the position of the center of resistance affecting initial tooth movement, so that the incorporation of information from plain radiographs, CBCTs, and dental models into the preexisting geometry of FE models was suggested [42, 43, 44•]. The importance of different levels of alveolar bone support on the mechanical behavior of the teeth has been assessed in case of periodontally compromised dentitions using FE models [45]: the type of OTM, the location of the center of resistance, and the stress and strain fields generated by simulated orthodontic forces are dramatically changing with a reduced alveolar bone support.

Whatever the type of model used, the results of FE analyses should ideally be compared to experimental in vivo data, in order to check their validity. Given the practical and ethical difficulties to validate FE models and given that only few experiments looked at tooth displacement under loading condition [20, 29, 46, 47], only a small number of authors performed indirect validation of FE models [48–52], mostly using animal data.

Mechanical Characteristics of the PDL

As mentioned before, the material properties of the PDL play a key role in simulating the correct behavior of a FE model in transferring the forces from the crown to the alveolar bone. Yet, the PDL is a tissue that is difficult to characterize experimentally, given its complex behavior related to the collagen fibers and ground substance (mostly fluid) components; thus there is a lack of comprehensive experimental data to characterize the PDL in all its hyperelastic, viscoelastic, and anisotropic responses.

In the literature, several attempts were made to describe the behavior of the PDL to be used in FE simulations.

1) In 2016, Huang H et al. proposed an exponential hyperelastic model [53] and validated this model against in vitro nanoindentation, obtaining a good match between the curve of the experimental test and the FE simulation.
2) McCormack and co-authors investigated the role of modeling the ligament fibers on the behavior of FE models, compared to modeling the PDL as a layer of solid material, when orthodontic and occlusal forces are simulated. The results showed that in order to truly depict the load transfer and the consequent strain field generated in the PDL and in the alveolar bone, modeling of the fibrous components seems to be necessary [17, 35].
3) In an in silico experiment where the nonlinearity of the PDL was modeled using a hyperelastic material approach, Nikolaus et al. also incorporated a regionally varying thickness of the PDL into their FE model [50]. They validated their model by comparing the calculated displacement of the tooth-PDL-bone complex to the results of animal experiments available in the literature. They concluded that their model, incorporating the micro-geometrical changes in the PDL thickness as well as a nonlinear behavior, was able to reproduce well the in vivo behavior of the PDL under masticatory load.
4) Contrarily to the previous paper, Abraha et al. concluded that varying the PDL's Young's modulus during chewing force simulations did not seem to have a large effect on the calculated global strains but only on the local strain close to the alveoli [51]. Thus, a precise modeling of the PDL only seems necessary depending on the scope of the hypotheses being tested.
5) Another approach was described by Tuna and co-workers [48] and by Van Schepdael and co-workers [54]. Instead of using a solid mesh, they opted for an analytical description of the PDL. In detail, Tuna et al. used a nonlinear contact model, while the model presented by Van Schepdael et al., based on the model presented by Provatidis in 2001 [55], used a model where the roots of the teeth were approximated to the shape of an elliptic paraboloid. Both models provided a good description of the overall behavior of the PDL, with the possibility to determine the strains within the PDL. Using these approaches, the demanding task of modeling the thin PDL using a solid mesh with the related challenges (i.e., either a poor mesh quality leading to low results accuracy or a very dense mesh requiring large computational power) is not necessary. These approaches might prove to be suitable ways for reducing computing time, especially when multiple teeth are involved in a FE simulation.
6) A more general description of "soft collagenous tissues with regular fiber arrangement," which included the PDL, has been proposed based on the tissue architecture at the nanoscale level and accounting for entropic mechanisms [56]. However, this model cannot be directly used in FE simulation of OTM as it does not consider viscoelasticity.

Other authors investigated the importance of the simplifications introduced in modeling the PDL on the overall accuracy of FE simulation, in particular to estimate the location of the center of resistance of teeth, in order to improve the therapeutic efficiency in OTM using computer simulations [57]. By assessing the extent of the differences between realistic FE models (both in respect to morphology and material properties) and simplified FE models (also regarding the thickness of the PDL), the authors concluded that simplified FE models (even based on standard volumetric scans) would be sufficient when the main goal is to predict only the approximate estimation of the position of the center of resistance during OTM only, with the advantage of short computation times. On the other hand, when enhanced precision is required, the nonlinear material behavior of the PDL and the accurate modeling of its geometry should be included.

In the literature, the majority of FE studies focused on the initial displacement of the teeth. In contrast, only few studies investigated the simulation of OTM in the long term, where the incorporation of alveolar bone remodeling in the FE simulation is taken into consideration: two studies looked at a single tooth [58, 59] and two others at multiple teeth [60, 61], with a last one where the interaction between brackets and archwire in a multiple teeth setting was considered as well [62].

A final area where FE simulations were applied in orthodontics assesses the possible correlation of the onset of root resorption with particular levels of stress and strain in the PDL and at the cement-PDL interface. A systematic review concluded that the type and amount of applied orthodontic load at the crown level have an influence on root resorption [63]. This correlation has been studied in silico by few authors: Field and co-workers [27] concluded that zones with a high level of calculated hydrostatic pressure (above the capillary blood pressure) correlate well with the zones where root resorption is seen. Their results are in agreement with what was found by Hohmann et al. [64] and more recently by Zhong et al. [65].

Conclusions

From the number of articles published in the last 10 years, it is clear that there is an increased interest in studying OTM with in silico approaches. Several FE studies have investigated OTM considering humans, nonhuman primates, and other laboratory animals. Though some of the "older" FE models did not include the PDL or its modeling was very simplified (mostly due to limitations in getting the actual morphology and/or material properties), many of the more contemporary articles have modeled the PDL using more advanced material properties and accurate morphology. The articles included in the present critical review clearly confirmed that an accurate modeling of the morphology and precise material properties of the PDL and the alveolar support tissues in general are prerequisites to obtain meaningful results. Indeed, it is known that imprecise PDL material properties may lead to inaccurate results, especially when linear elasticity is used [56]. Having said that, there are particular computational intensive applications (e.g., quick estimation of OTM during treatment planning; simulation of long term OTM) where a proper balance between accuracy of the material properties of the PDL and simplifications can be introduced without compromising the results [18••].

Due to the complex mechanical behavior of the structures involved in OTM, combining the biological knowledge with an engineering approach can lead to new explanations of the basic mechanical activation mechanisms in respect to the biological signaling pathways leading to OTM.

The present review focuses on the different ways FE simulations have been performed. What is clear is that the loading pattern seen during the first phase of OTM can be seen as a direct consequence of the mechanotransduction mechanism leading to the re-arrangement of the PDL and bone resorption and formation. These findings do not corroborate the simplified view of the classical "pressure-tension" theory, nor the "bone bending theory," given the small magnitude of the strains related to orthodontic force application. The fact that orthodontic forces are static by definition suggests that the interaction between orthodontic and occlusal chewing forces, together with the presence of microstructural high strains, can be a possible explanation of how OTM is initiated. A realistic characterization of the material properties of the PDL to be used in FE simulations yet involving the least computational needs is also needed. Thus, it seems that more research to confirm the precise way these mechanisms are working is needed, also in the light of what has been described before in relation to the direct or undermining resorption [11, 66].

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

Human and Animal Rights and Informed Consent This article does not contain any experiments with animal subjects. The reported studies with human subjects performed by the authors complied with all applicable ethical standards (including the Helsinki declaration and its amendments, institutional/national research committee standards, and international/national/institutional guidelines).

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