European Journal of Orthodontics, 2017, 1–6
doi:10.1093/ejo/cjx041

Original article

Corticotomy affects both the modus and magnitude of orthodontic tooth movement

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Summary

Objective: To analyze whether the decreased bone density due to the manipulation of bone remodeling rate has an influence on the type of the planned tooth movement.
Materials and methods: A finite element model of a lower incisor has been developed. The density of the alveolar bone surrounding the tooth has been assumed to simulate the one occurring after corticotomy to increase tooth movement rate. Moment-to-force ratios corresponding to three different types of movements have been simulated; uncontrolled tipping, translation, and root movement. The three tooth movements have been analyzed in both corticotomized and non-corticotomized simulations, and the final effects on the amount and type of tooth movement analyzed. The stress and strain levels in the periodontal ligament have been analyzed too.
Results: The amount of tooth movement obtained in case of lower bone density is higher in all types of movement simulations. The centre of rotation of the movement shifts more apically in case of translation, controlled and uncontrolled tipping. In the corticotomy simulations, the compressive stresses in the periodontal ligament decreased while the tensile stresses increased.
Conclusion: A decreased bone density influences not only the amount of tooth movement, but also its type. This study suggests that the moment-to-force ratios used in conventional orthodontics should be modified in case of techniques that decrease bone density to enhance tooth movement rate.

Introduction

The reduction of the orthodontic treatment time is convenient for both clinicians and patients. A short treatment duration would be particularly advantageous in cases of severe malocclusion, as in cases of ectopic canines. Tooth substance demineralization and root resorption may affect patients with fixed appliances and have been found to be time-dependent (1). Therefore, it might be possible to reduce the prevalence of these side effects by decreasing treatment duration. Additionally, shorter treatment duration would facilitate the patient compliance towards the overall treatment.

Several approaches able to influence the bone biology that is behind orthodontic tooth movement, maximally or minimally invasive, have been increasingly suggested in the last decade (2). Increase bone remodelling rate is known to increase tooth movement rate in animal studies (3, 4). It has been seen that fiberotomy alone is able to modify the local bone remodelling rate and to increase tooth movement rate in a rat model (5). The increase of bone remodelling rate through the regional acceleratory phenomenon (RAP) is used to accelerate tooth movement through cortical/periosteal/periodontal stimulation with different techniques with variable invasiveness (2, 6). The RAP that occurs after corticotomy is seen as a fracture healing process, and the magnitude of the response is directly proportional to the size of the injury (7, 8). It has been suggested that the higher turnover generated by the RAP will temporarily decrease bone density and the stress levels in the periodontal ligament, reducing, as a consequence, the root resorption occurrence (9, 10). The radiological evaluation of bone density in humans and in a rat model has shown a decrease between 41 and 55 per cent of the baseline bone density after corticotomy (11, 12). Despite the transient decreased bone density,

bone resorption and formation activities remain coupled (12). The RAP is by definition a local reaction and it has been seen in a thorough histological animal study that it rarely extends more than a one tooth distance (13). A decreased bone density modifies its mechanical properties (14) and the result of the application of a biomechanical system may depend on the resistance offered by the surrounding tissues (15). Although at a low level of evidence, surgically assisted orthodontics may increase the speed of orthodontic tooth movement, especially in the first months (2, 16). However, the consequence of it on the biomechanics of the movement has not been considered yet.

The aim of this study is to evaluate, through a finite element analysis, the effect of reduced bone density on the magnitude and type of orthodontic tooth movement and the related stress-strain distribution in the periodontal ligament. The hypothesis to be tested is that the RAP does not influence the amount and the modus of orthodontic tooth movement nor the distribution of the stresses and strain in the periodontal ligament.

Materials and methods

A Finite Element (FE) model of a mandibular central and lateral incisor was created using a 3D micro-computer tomography data-set of a jaw section of a 20-year old male donor, which had been made available for a previous study with approval of the local ethical committee (17).

Creation of the FE model

Using dedicated image analysis software (Mimics, version 18.0 including the FE-module; Materialise, Leuven, Belgium) the data-set was segmented by selecting the hard tissues, and reconstructions of the teeth and bone were created. Using the image analysis software's Boolean tool, the periodontal ligaments (PDL) were created as the volumes between the roots and the alveoli. In addition, an area in the shape of a buccal bone flap was selected where a corticotomy without flap (18) was simulated to have taken place (Figure 1). The whole buccal plate corresponding to the buccal surface of the root was considered as regionally affected by the corticotomy (13). As seen in Figure 1, most of the alveolar bone in this area is composed by cortical bone. From these 3D objects, FE models consisting of 35 934 nodes and 207 324 tetrahedral elements were generated. Material properties of the various tissues were assigned according to Table 1 (19, 20). Using the image analysis software's material property assignment tool, the centroid of each element representing bone was assigned a grey value corresponding to the grey value of the closest located voxel from the original micro-CT data-set. The values of the Young's moduli of bone marrow and cortical bone originate from the work of Carter and Hayes (21). Blok *et al.* found volume fractions up to 0.5 in the anterior part of the mandible in their study on the density of alveolar bone (22). This value combined with cubic relationship between Young's modulus and apparent density described by Carter and Hayes and later adjusted by Blackburn and Hodgskinson yielded the value for the Young's modulus of cancellous bone (21, 23) to be in the order of 3000 MPa. The corresponding bone density would be 0.75 g/cm^3. When the RAP reduces this density by 41 per cent (11), the resulting density would then correspond to a Young's modulus of 500 MPa. The FE models of the various tissues were individually exported in so-called NASTRAN bulk file format and rejoined in the FE software (Strand7, version R2.4.6; Sydney, Australia) for the actual analyses.

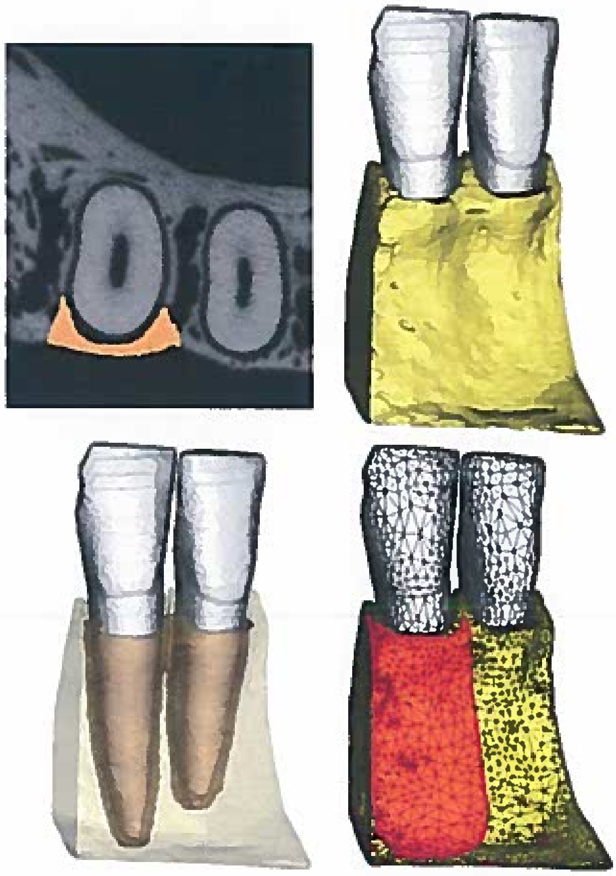

Figure 1. The geometry of a section of a mandible containing a central and lateral incisor used for the FE models: a micro-CT scan midway the roots (top left), the control model (top right), the control model in transparency to show the PDLs and roots (bottom left) and the model with the buccal corticotomy (marked in orange) on the lateral incisor (bottom right). The low bone density material properties were assigned to both the trabecular and the cortical bone components of the area in which the RAP phenomenon (orange area) was simulated.

Table 1. Material properties given to the different structures.

	E (MPa)	*n*
Teeth	20000	0.30
bone marrow	200	0.45
cancellous bone	3000	0.30
cortical bone	16000	0.30
corticotomized bone	500	0.33
PDL	variable*	0.45

E = Young Modulus, MPa =megaPascal, *n* = Poisson Modulus

Preprocessing of the FE model

As boundary conditions, nodal movements in the mesial/distal aspect were suppressed at the mesial and distal end plates of the models as well as apical/coronal movements for all nodes on the bottom end plate of the models.

External loading conditions simulated an orthodontic loading of the lateral incisor using a range of moment-to-force (M/F) ratios with a buccal force and a lingual tipping moment, both applied at the middle of the buccal surface of the crown, where normally a bracket would be placed. Basically, the choice of these loading cases was aimed to recreate the curves presented by Burstone and

Pryputniewicz, showing the dependency of the distance between the centre of resistance (CR) and centre of rotation (C_{rot}) and the applied M/F-ratio at the bracket (24). A force of 32 cN was chosen.

Due to the non-linear material properties of the PDL tissue (25), the analyses were performed using the non-linear static solver (material non-linearity).

Postprocessing of the FE model

After the analyses, the displacements of a point on the incisal edge of the crown of the lateral incisor and another at its apex were used to construct the location of the C_{rot} for that particular load case. Compared to the deformations of the PDL, the incisor is moving like a rigid body and its C_{rot} can be calculated as the intersection of the lines perpendicular to and through the middle of the two aforementioned displacements vectors. The location of the CR, which is invariant for all load cases, was similarly found as the C_{rot} of a single applied tipping moment. In addition to the displacements of the lateral incisor, the stresses and strains of its PDL were evaluated to study the load transfer there across.

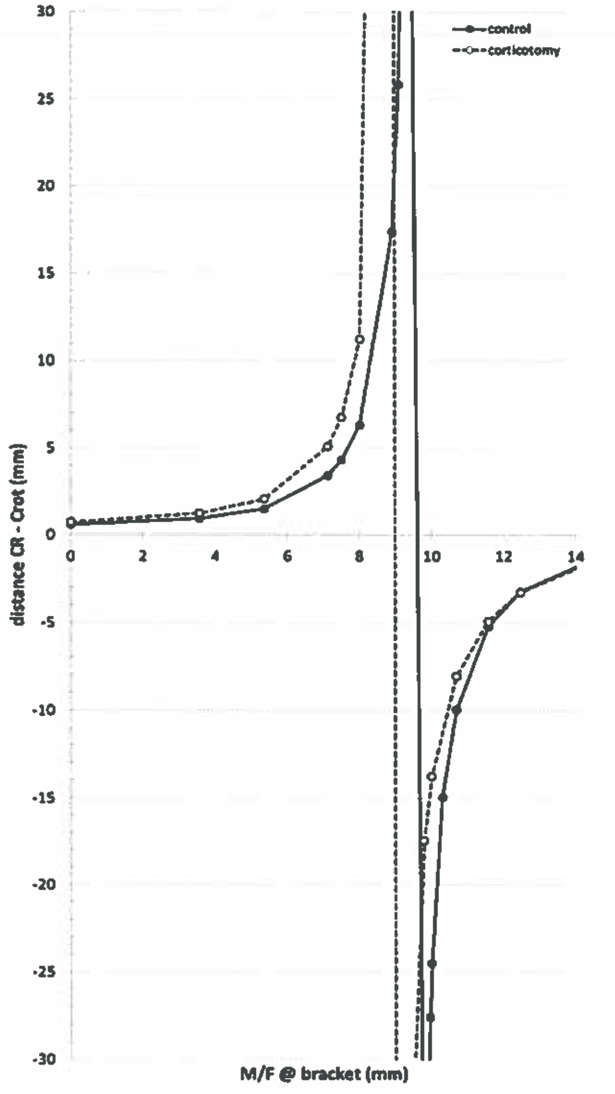

Figure 2. The "Burstone & Pryputniewicz" curves showing the dependency of the distance between CR and C_{rot} of the lateral incisor and the applied M/F-ratio for both the control and corticotomized models (24) (Burstone and Pryputniewicz).

Results

Corticotomy affects the relationship between modus of orthodontic tooth movement and the applied M/F-ratio. The "Burstone & Pryputniewicz" curves of the control and corticotomized lateral incisor show marked differences (Figure 2). The M/F-ratio where the curve dives from infinity to minus infinity (the situation of pure translation) is lower for the corticotomized tooth than for its normal control. Also, the width of the area between shooting off to infinity and coming back from minus infinity is broader for the corticotomized tooth than for its normal control.

Not only the modus of tooth movement is affected, but also the amount of tooth movement, which is made visible using deformed plots, is influenced by a corticotomy. There is more tooth movement in case of a corticotomized tooth (Figure 3). Combining the modus and amount of tooth movement, the shift of lower M/F-ratios for corticotomized teeth to achieve controlled tipping, pure translation and root movement is visualized in Figure 4. In general, the tooth movement is larger for the corticotomized tooth, especially for the uncontrolled tipping. Furthermore, the M/F-ratios for which pure controlled tipping, pure translation and pure root movement occur are generally 0.5 to 1.0 mm lower for the corticotomized tooth, as also illustrated in Figure 2.

The way the lateral incisor moves, also affects the loading of its PDL. For the corticotomized tooth, where the bone on the buccal side has been reduced in stiffness, during uncontrolled tipping the tensile stresses are more pronounced at the lingual cervical area, whereas in the control tooth tensile stresses are more symmetrically distributed in the lingual cervical and buccal apical areas. (Figure 5). The higher tensile stresses are not only restricted to the uncontrolled tipping. Also for the other M/F-ratios, the tensile stresses are larger for the corticotomized tooth (Figure 6). The compressive stresses in the PDL are larger for the control case, as the more flexible bone at corticotomy works as a soft support.

Discussion

The surgical techniques that facilitate orthodontic tooth movement base their effect on the decreased bone density and the enhanced turnover.

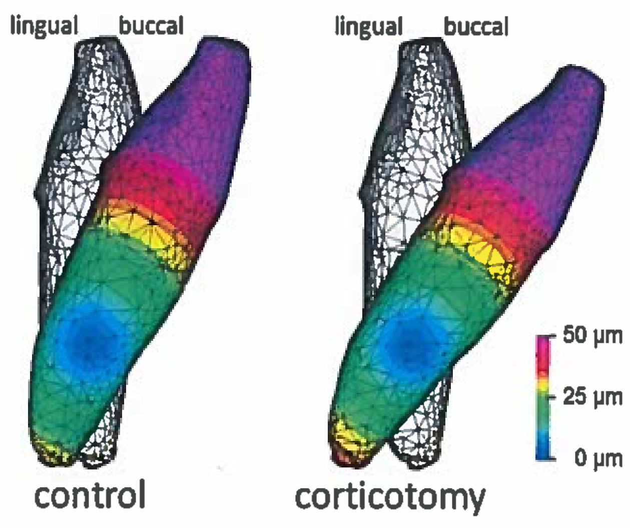

Figure 3. The total displacement of the lateral incisor in case of an uncontrolled tipping (M/F = 0) for both the control and corticotomized models (with a deformed plot scaling factor of 100×). The centres of the dark areas correspond to the C_{rot}.

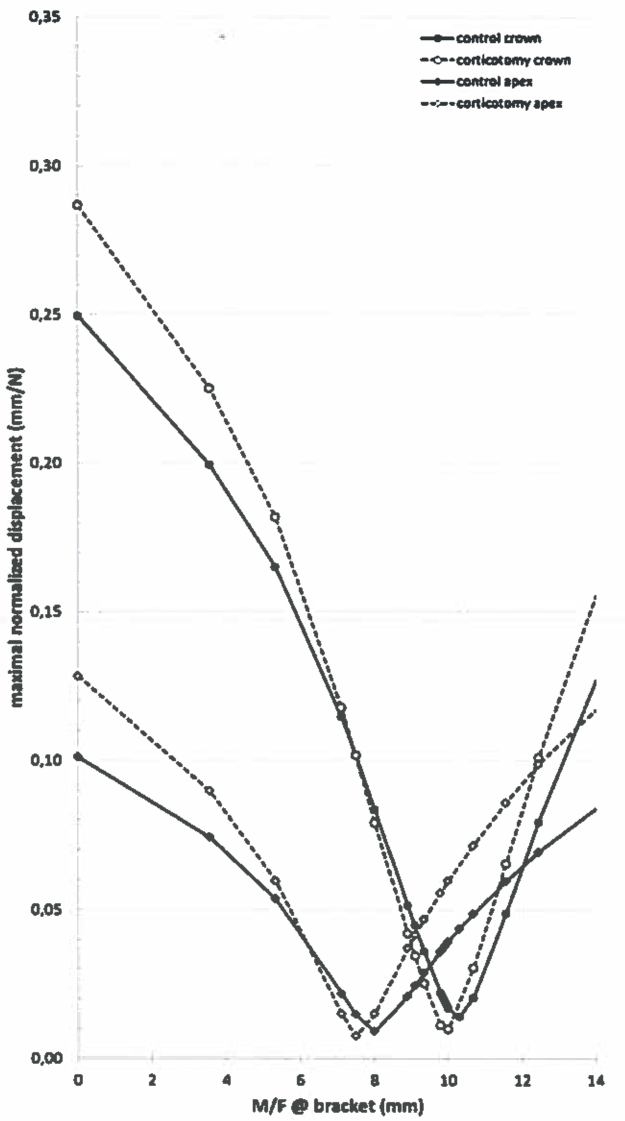

Figure 4. The displacement curves of the top of the crown and apex of the lateral incisor depending on the applied M/F-ratio. Note that where the apex curve reaches its minimum a pure controlled tipping occurs; where the crown and apex curve intersect for the first time a pure translation occurs. The second intersection corresponds to a type of uncontrolled tipping, whereby the apex and crown move equally, yet in opposite directions. Where the crown curve reaches its minimum a pure root movement occurs.

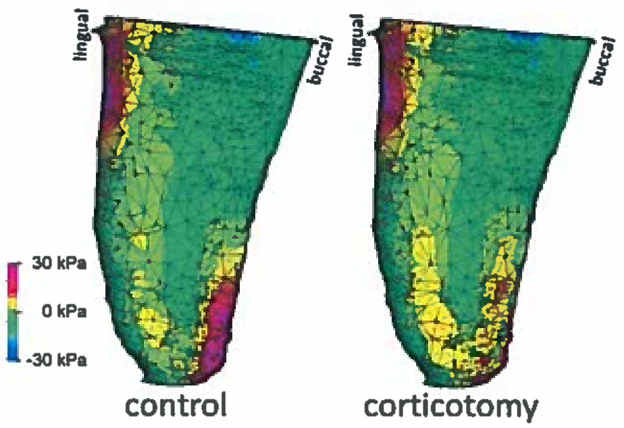

Figure 5. The buccolingual stresses in the PDL of the lateral incisor in case of an uncontrolled tipping (M/F = 0) for both the control and corticotomized models. Note that the control PDL features tensile stresses both at the lingual cervical area and the buccal apical area, while for the corticotomized PDL the stresses in the lingual cervical area are increased, while in the buccal apical area they are reduced. The control PDL also features higher compressive stresses along its buccal cervical rim than the corticotomized PDL.

The type of tooth movement obtained by an appliance depends not only on the moment and forces applied, but also on the level of the supporting tissues, as in the case of periodontally compromised teeth.

Several clinicians suggest the use of surgically facilitated therapy in association with invisible aligners with built-in displacements information. However, the question if the appliance has to be programmed differently in cases of surgically facilitated tooth movement has not been addressed, and it is empirically suggested to change the aligners more often, at an interval subjectively decided by the clinician. The lack of information concerning possible biomechanical consequences of biological 'manipulation' of bone are also lacking in fixed mechanics.

The biomechanics of tooth movement in relation to surgically facilitated tooth movement has been studied until now with finite element analysis only by Yang *et al.* (26). However, in their model the material properties of the periodontal ligament have been considered to be linear-elastic, which has been shown not to be correct for the load transfer across the periodontal ligament (27). Moreover, the potential influence of a decreased bone density on the tooth displacement has not been taken into consideration. The present FE-analysis has shown an influence of alveolar bone density on the modus and amount of tooth movement. Before this issue is further explored, however, a quick remark on which type of tooth movement has been analysed in the present study. Strictly speaking, it is the movement of the tooth within the alveolus when a viscoelastic steady state in the PDL has occurred, some hours after the application of the orthodontic load. The long-term orthodontic tooth movement, due to remodelling of the alveolar bone has not been analysed, although initial and eventual tooth movement are related.

The M/F-ratio, where the curve dives from infinity to minus infinity (the pure translatory movement), is lower for the corticotomized tooth than for its normal control, as shown in Figure 2. Therefore, to achieve the same movement the application of a lower M/F is needed, i.e. pure translation is reached in case of corticotomy with the same M/F used to obtain controlled tipping without corticotomy.

Also the width of the area between shooting off to infinity and coming back from minus infinity is broader for the corticotomized tooth than for its normal control. The ranges of M/F-ratios that allows a translation in the case of corticotomy is from 8 to 10, while for the control it is from 9.10 to 10. This means that the load transfer mechanism is more forgiving when aiming for a pure translation in case of corticotomy. As seen in Figure 5, the centre of rotation of the dental displacement moves, in case of corticotomies, more apically. A similar result was obtained in an *in vivo* model in rats, found that the application of a single force at the level of the crown generated a controlled tipping in case of reduced bone density (28). If we consider our finding together with the fact that the centre of rotation has been found to be root-shape-related (19), the validity of systems that pretend to predict tooth movement in an average way has to be discussed.

Those results confirm the clinical finding that corticotomies enhance tooth movement rate, especially in cases of uncontrolled tipping, while translatory movements tend to happen at the similar pace. As a clinical consequence, the treatments that require tipping will profit more of corticotomies than other movements.

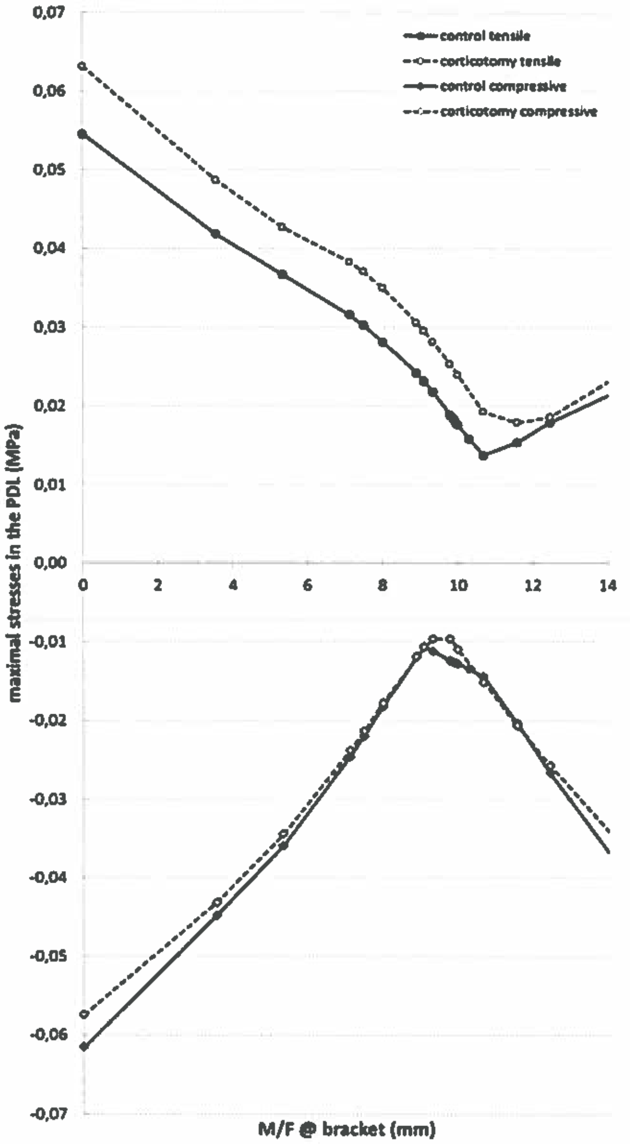

Figure 6. The buccolingual tensile and compressive stress peaks in the PDL of the lateral incisor depending on the applied M/F-ratio. Note that the tensile stresses are higher in the corticotomized model, whereas the compressive stresses are higher for the control model.

It has been claimed that surgically facilitated orthodontic tooth movement decrease the rate of root resorption, by decreasing the loading in the periodontal ligament and, therefore, reducing the occurrence of hyalinization (29), the latter being related to orthodontically induced root resorption (30). This study confirms a lower level of compressive stress in the periodontal ligament in the corticotomized teeth, although the levels do not reach the one of capillary vessels. This may be due to the model of corticotomy, in which we decreased the bone density only in the corticotomized segment, whereas the surrounding bone did not decrease in density.

It could be argued how representative a FE model, based on the anatomy of a single tooth from a single donor, is for the mechanics of single-rooted teeth in general, since the individual anatomy greatly determines the load transfer. The same can be said for the assignment of the material properties for the various hard and soft tissues in the model, which also varies on an individual base. However, the aim of this study was to investigate on the sole variable of bone density. The FE-analysis is an appropriate tool to answer this question (31). The strength of an FE-analysis is to be able to vary one aspect in the model (in this case the absence or presence of a buccal corticotomy), leaving everything else unchanged. The observed differences in the outcome are then purely due to the applied variation and unbiased conclusions can be drawn up about the effect of, in this case, a buccal corticotomy, which is not possible *in vitro* or *in vivo*. Once established the influence of a first variable, as the low bone density given by the RAP phenomenon, other variables can be added in the model, as individual variation within the same anatomical areas in relation to facial morphology or differences between anatomical areas, such as lower incisors or lower molars.

The use of similar models to other root morphologies and anatomical environments would allow, therefore, for a better insight into the biomechanical consequences of induced low bone density during orthodontic load application.

Conclusion

To conclude, this study has shown that the decreased bone density induced by surgery to facilitate tooth movement not only influences the amount but also the modus of tooth movement. As a clinical suggestion, the planning of the biomechanical system to apply, fixed or removable, has to be modified accordingly.

Further FEM studies are required in order to study the role of different bone thicknesses and alveolar bone areas, in combination with more or less invasive surgical procedures.

Conflict of interest

None to declare.

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