Original article

Three-dimensional finite-element analysis of a central lower incisor under labial and lingual loads

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Abstract

Introduction: The aim was to evaluate the differences between labial and lingual application of an orthodontic force. This was achieved using a three-dimensional CAD design software model of a real lower incisor surrounded by a prismatic representation of the mandibular bone. This model was subjected to various loading conditions, with finite-element analysis.

Materials and methods: Cone-beam computed tomography scanning was used to create a three-dimensional geometric model of a lower incisor, together with its simulated periodontal ligament. This model was then meshed and analysed with commercial finite-element code. Various single and combined forces and moments were applied to each side of the simulated lower incisor at the centre of the clinical crown. To evaluate the effects of the various forces considered, the instantaneous displacement and stress generated in the bone and the periodontal ligament were measured, as a comparison of the labial and lingual loading sites.

Results: Dental movement was only influenced by the side of the force application when an intrusive component was present. The simulations showed larger displacement when a vertical force was present at the lingual surface. In general, this movement was of the tipping type when the combined forces were applied, while there was greater intrusion upon application of combined forces and an anticlockwise moment to the labial surface.

Conclusions: Application of an intrusive lingual force to a lower incisor appears to generate bodily movement, while the same intrusive labial force appears to lead to labial tipping. Subject to further study, this should be taken into consideration when devising treatment plans for fixed appliances.

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1. Introduction

Continuous application of an orthodontic force to a tooth triggers remodelling in the surrounding bone, which eventually leads to tooth displacement. On a biological level, dental displacement appears to be brought about by catabolite recruitment, as deformation of the trabecular bone generates a change in its metabolism. From a biomechanical perspective, numerous studies have sought to characterise how this dental movement is brought about. In particular, Sandstedt documented the formation of new tissue on the side of the tooth where the periodontal fibres were under tension, whereas bone resorption occurred in the same fibres on the side of the tooth where compression was applied. On the other hand, Ren et al. explored continuous application of orthodontic forces of various intensities, and reported that the rate of dental displacement over time in response to these orthodontic forces shows considerable individual variation. Therefore, according to the speed of the dental displacement, patients can be classified as ‘fast movers’ or ‘slow movers’.

This is particularly important when planning orthodontic treatment that involves fixed appliances. Indeed, following many more recent advances in the field, clinicians now have access to a wide variety of high-quality techniques. In particular, the growing emphasis on aesthetics means that the lingual technique has reached a similar level of application and development as the more conventional labial orthodontics. In addition to their relative unobtrusiveness, lingual appliances obviate the need for etching the labial enamel, and the displacement of each tooth can be observed more clearly, with respect to the labial technique. However, the typical greater variability in tooth anatomy on the lingual side of the dental arch can make the positioning of the bracket difficult, which can have a profound influence on the biomechanics of this lingual approach. In this respect, the main difference between the labial and lingual techniques is the distance between the point of application of the force that is transmitted through the bracket and the centre of resistance of the tooth. Consequently, the displacement and stress induced in bone by these two techniques will also differ, and these need to be evaluated so that useful comparisons can be made between these techniques.

Although biomechanical forces are relatively difficult to measure directly, analysis using the finite-element method (FEM) can provide useful estimates. Indeed, as an example, the FEM has already been successfully used to evaluate the state of stress generated by palatal miniscrews, to determine their ideal implantation sites. Furthermore, the FEM approach has been used to provide a convincing evaluation of the stress distribution in tooth roots, the periodontal ligament, and the trabecular bone upon the application of different loads.

However, to the best of our knowledge, no FEM studies have been carried out on lower incisors to compare the effects of such forces on lingual and labial bracket-placement sites. Despite this, some studies have assumed that there are indeed differences here. We therefore designed a FEM geometric model of a lower incisor, its supporting trabecular bone, and its surrounding periodontal ligament, to evaluate and compare the biomechanical responses to forces mimicking those generated by both lingually and labially positioned brackets. To create this workable model, we used an actual ex-vivo lower incisor, with cone-beam computed tomography scanning of its anatomy to obtain a digital three-dimensional rendering. To obviate interference from the actual soft tissues, the surrounding bone was generated using three-dimensional CAD design software. This model was subjected to FEM simulations to evaluate the effects of loads that would be generated by a bracket positioned on each side of the crown of the lower incisor.

Initially, each force was analysed individually, to better compare the effects for the two sides of the force application. Subsequently, however, to better approximate the complex reality of bracket loading conditions, combinations of several simultaneous forces were analysed. We thus report here on the considerations relating to the mechanical effects of each type of simulated treatment.

2. Materials and methods

A whole lower incisor that was sterile and devoid of caries was mounted on a wax support and scanned by cone-beam computed tomography using a NewTom 3G (Qr Srl, Verona, Italy). The following settings were applied: 110 kV, 0.50 mA, 12-inch field-of-view, and 5.4-second exposure time. According to the manufacturer specifications, the voxel was an isometric cube with an edge length of 0.3 mm. To maintain optimum image clarity and to minimise interference produced by the surrounding soft tissues, an experimental model was chosen for this initial investigation, rather than a real patient.

Mimics (Materialise, Leuven, Belgium) and SolidWorks CAD (DS SolidWorks Corp., Massachusetts, USA) three-dimensional design software were used to create a solid model of the lower incisor from the cone-beam computed tomography images. The CAD software was also used to construct a prismatic bony region of $20 \times 15 \times 10$ mm around the lower incisor comprising both the trabecular and cortical bone, as well as the periodontal ligament and alveolus. The compact bone and the periodontal ligament layers were designed to be irregular in shape, so as to conform to the shape of the lower incisor. The compact bone layer was 0.5 mm thick on average, while the periodontal ligament layer had a thickness ranging from 0.1 mm to 0.5 mm. The lower incisor was placed virtually in the alveolar cavity, with an angle of 110° created with respect to the occlusal plane, to reflect a typical clinical case. The geometric model was then imported into the ANSYS Workbench platform (ANSYS, Inc., Canonsburg, Pennsylvania, U.S.A.) for the FEM simulations (Fig. 1).

Due to the irregular geometry, the geometric model was discretised with non-linear tetrahedral elements, each of which had ten nodes (i.e. the TET10 element). The mesh was refined at the points where gradients were expected (e.g. at the material interfaces) and was left coarse elsewhere, to avoid unnecessary use of computation time. The final mesh had a total of 35,684 elements and 67,133 nodes. All of the
Fig. 1 – The geometric model. The different colours correspond to the tissues simulated, i.e. cortical bone (yellow), trabecular bone (green), periodontal ligament (dark grey) and dentine (light grey). Z is the labiolingual axis.

<table>
<thead>
<tr>
<th>Material</th>
<th>Young’s Modulus [MPa]</th>
<th>Poisson Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dentine</td>
<td>19600</td>
<td>0.31</td>
</tr>
<tr>
<td>Cortical bone</td>
<td>13700</td>
<td>0.3</td>
</tr>
<tr>
<td>Trabecular bone</td>
<td>1370</td>
<td>0.3</td>
</tr>
<tr>
<td>Periodontal ligament</td>
<td>0.667</td>
<td>0.45</td>
</tr>
</tbody>
</table>

Fig. 2 – Forces applied to the lingual and labial sides of a lower incisor: 1) labiolingual; 2) linguolabial; 3) mesial rotation; 4) distal rotation; 5) intrusion.
1 N (100 g), an intrusive force of 0.64 N (64 g), and an anticlockwise moment of 0.5 N mm were used (Fig. 4), which were applied to both the labial and lingual sides (case 8).

To quantify the dental movement in response to these forces, the instantaneous displacement of the lower incisor in the labiolingual direction was considered, i.e. the displacement immediately after the loading was applied. It is important to notice that this is different from the final displacement of the tooth, as it occurs before the remodelling of the surrounding bone tissue and it will necessarily be much smaller. Nevertheless, we hypothesised in this initial study that although different in magnitude, this immediate displacement will be proportional to the final displacement, thereby allowing considerations for the total movement of the lower incisor and comparisons of the various loading conditions.

As the state of stress that would be generated in the ligament and the surrounding bone by the movement of the lower incisor is a determining factor for bone remodelling, the stress in the labiolingual direction was also evaluated. The benchmark value of 3.3 kPa, which corresponds to a pressure of 25 mmHg, is given in all the figures, as this is believed to be essential for the triggering of the processes of bone remodelling. Indeed, the well-known theory of Schwarz, which confirmed the discoveries of Sandstedt, defined the optimal force as that which causes pressure variations in the periodontal ligament without occluding the capillaries. As the capillary pressure is from 20 g/cm² to 26 g/cm², this is considered to be optimal. However, it should be noted that Ren et al. could not define an optimal orthodontic force in their study of the application of continuous forces of various intensities.

### 3. Results

The maximum instantaneous displacement vectors caused by the application of forces to the lower incisor in cases 1-5 were in the direction of the forces themselves, and these are reported in Table 2. These values were very similar in cases 1-4, irrespective of the application site (lingual or labial), while there was a marked difference in case 5, although the values are very small in all cases.

Considering case 1, Figure 5 shows the comparison of the dental displacement in the labiolingual direction upon...
Table 2 – Absolute values for the maximum displacement in the direction of the force applied in the scenarios considered.

<table>
<thead>
<tr>
<th>Maximum displacement in the direction of the force applied [µm]</th>
<th>Labial application</th>
<th>Lingual application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>Case 2</td>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>Case 3</td>
<td>0.25</td>
<td>0.26</td>
</tr>
<tr>
<td>Case 4</td>
<td>0.25</td>
<td>0.26</td>
</tr>
<tr>
<td>Case 5</td>
<td>0.08</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Fig. 5 – Displacement [mm] in a labiolingual direction in Case 1. Left: Labial application. Right: Lingual application.

application of the single force to the labial or lingual sides of the lower incisor. The normal stress in the same direction ($\sigma_2$) in the alveolar region for the same case 1 is shown in Figure 6. In both of these analyses, the lower incisor displacement is concentrated in the crown of the lower incisor, with virtually none in the apical region, which indicates a tipping movement. Moreover, Figure 6 shows a trend in the stress generated that conforms to this type of dental movement, i.e. it shows two regions of compression, in the upper and lower thirds of the apical region.

In the interest of brevity, the results obtained for cases 2-4 are not reported individually, as they all showed maximum displacement as localised at the incisal border of the crown of the lower incisor, with far lower, and almost negligible, values at the apex. Thus, the fulcrum of the displacement is again at the apex, in proximity to the centre of displacement, and this also causes a rotational, i.e. tipping, movement in these cases. Likewise, the tensile states are analogous, irrespective of the side of the force application to the lower incisor.

Interestingly, the results for case 5, i.e. intrusion, reveal a different distribution between the two sides of application (Fig. 7). Indeed, when the force was applied labially, the trend was similar to that reported for case 1, albeit to a lesser extent. However, the lingual application resulted in the displacement of the upper and lower thirds of the lower incisor in the same direction as the force, while the central portion of the lower incisor moved in the opposite direction. In this case, the displacement trend in the direction of the force applied (downwards) can provide useful information about the dental displacement. Indeed, the labial force application led to regional differences in the downwards movements, which is suggestive of tipping. However, upon lingual application, only two areas were displaced, and to very limited degrees, thereby indicating that this lingual application of the force induces only limited bodily intrusion.

Figure 8 shows a comparison of the stress states in case 5, upon labial (Fig. 8, left) and lingual (Fig. 8, right) application of the force. When the force was applied labially, zones of compression were evident in the upper and lower thirds of the alveolar region of the lower incisor, confirming its tipping. The lingual application of the force, on the other hand, generated a more generalised compression throughout the alveolar area of the lower incisor, thereby indicating bodily intrusion.

For the cases with combined forces, Figure 9 shows the immediate displacement of the lower incisor for case 6. When the forces were applied to the labial side of the lower incisor, the displacement was greater, thereby leading to more pronounced rotation. Figure 10 shows the stress states in a labiolingual direction in the bony region for the lower incisor. In both cases, the stress trends are very similar, although
larger regions of compression are seen when the force is applied lingually; here, rotation was impeded by the anatomical features that blocked the movement of the lower incisor, thereby generating greater stress in the surrounding areas.

Figure 11 shows the instantaneous displacement of the lower incisor for case 7. Here, the displacement indicated a tipping movement, irrespective of the side of application, although it was seen to be greater for the lingual force application. This is confirmed by the trend in stress shown in Figure 12, where there are larger regions of stress when the forces were applied labially and the displacement of the lower incisor was impeded.

Figure 13 shows the immediate displacement of the lower incisor in case 8. The movements observed, which apparently included tipping, were very similar. Figure 14 shows the stress state in the labiolingual direction in the bony region, which reveals compression of the entire area due to the intrusion of the lower incisor following the labial force application, and an apparent rotation when the force was applied lingually, as seen by the zones of compression.

4. Discussion

The objective of the present initial study was to compare the biomechanical responses to labial and lingual application of
Fig. 10 – Stress (σ2) in a labiolingual direction [MPa] in Scenario 6. Left: Labial application. Right: Lingual application.

Fig. 11 – Displacement in a labiolingual direction [mm] in Case 7. Left: Labial application. Right: Lingual application.

Fig. 12 – Stress (σ2) in a labiolingual direction [MPa] in Case 7. Left: Labial application. Right: Lingual application.

Fig. 13 – Displacement in a labiolingual direction [mm] in Case 8. Left: Labial application. Right: Lingual application.
an orthodontic force on a lower incisor. To this end, we evaluated the instantaneous displacement of the lower incisor through the FEM. To complete the picture, the stress distribution within the surrounding bony support was also calculated, to identify regions of tension and compression. As these measurements in actual patients would be hampered by the variability in their tissue responses and by the dental anatomy itself, a bespoke three-dimensional FEM model was created that featured both the lower incisor and the alveolus.

To perform the FEM analysis, some simplifying assumptions were made. In this respect, perhaps the most critical point is that the result of the FEM simulations is not the final displacement of the lower incisor at the end of the orthodontic treatment, but rather the immediate displacement after the application of the forces. It is clear that the final tooth displacement depends heavily on the remodelling phenomena that occur within the bone tissue that supports the lower incisor, but these were not considered in the present study. Indeed, these are still considered to be unresolved issues in biomechanics. Although precise quantification of the final movements of the lower incisor cannot be obtained with the present approach, useful comparisons under the various loading conditions can be drawn on the assumption that the final lower incisor displacement is proportional to this initial displacement.

Secondly, the simulated lower incisor was embedded in a bone block that is just a rough representation of an authentic alveolar site, even though it was designed according to the material properties of the trabecular and cortical portions, and of the periodontal ligament. This approach clearly simplifies the numerical analysis, as the geometry is easier. However, it does not consider the possible interactions between different teeth during this orthodontic treatment, which will undoubtedly be an important factor. Nonetheless, it must be borne in mind that the stress state in an elastic solid that is loaded in a relatively small region (like the bone tissue holding the lower incisor in our analysis) decays with distance according to the cube of the distance.  

Finally, all of the materials were assumed to be linearly elastic, thereby simplifying the numerical analysis. While such a hypothesis may be appropriate for bone, dentine and enamel, the periodontal ligament, as a soft tissue, should be considered a non-linear, perhaps even viscoelastic, material. Nevertheless, for the purpose of the present initial analysis, the hypothesis of linearity appears to be reasonable due to the small strains in the periodontal ligament which never exceeded 0.07% to 0.10%.

When this model underwent various simulations to highlight the differences according to the side of application of the force to the lower incisor, the findings showed substantial differences in four of the cases. For the cases in which single forces were applied (cases 1-5), the only differences were noted for an intrusive force (i.e. case 5): there was a more bodily dental displacement when the force was applied to the lingual surface of the lower incisor. This confirms the findings documented in the literature, and particularly those reported of Ryoon et al., in their prospective clinical study: i.e. intrusion of the lower incisors is more effective when the lingual mechanics are exploited. Furthermore, in the same study, and in agreement with Schudy et al., it was confirmed that the correction of labial overbite using continuous wire occurs through the extrusion of the posterior sectors and the labial displacement of the incisors, with minimal incisor intrusion. This demonstrates that the application of a force with an intrusive component to the lingual surface of an incisor will bring it closer to the centre of resistance.

Different displacements did, however, result from labial and lingual application of the combined forces to the lower incisor. Indeed, with the loading towards the exterior in case 6, this resulted in greater rotation when the combined force was applied labially to the lower incisor, while in case 7, with the loading towards the interior, there was greater rotation when the combined force was applied lingually to the lower incisor.

Finally, for consideration of the most complex case in which the lower incisor was subjected to forces and moments acting in labiolingual, downwards and anticlockwise...
directions, the labial application mainly caused a bodily retrusive movement of the lower incisor, whereas the lingual application generated tipping, with an apical centre of resistance.

Among others, Liang et al.,24 also reached the same conclusions. i.e. that bodily (translatory) displacement of a tooth is favoured by the application of the force to the labial side.

5. Conclusions

In the present study, various FEM simulations were used to evaluate the differences in the mechanical responses to various types of force-loading conditions. These conditions parallel the application of an orthodontic bracket on the lingual or labial side of an anatomical system that comprises a lower incisor and its corresponding alveolar region. The results were the following:

- When single forces are applied to the lower incisor, a tipping displacement is generated, irrespective of the point of application, except when an intrusive force is applied to the lingual side.
- When combined lingual and intrusive forces are applied to the lower incisor, it is displaced in a labial direction, irrespective of the side of application.
- When combined labio-labial and intrusive forces are applied to the lower incisor, the tooth displacement is essentially reminiscent of tipping, irrespective of the side of application. This finding is confirmed by the trend in stress observed around the dental surface.
- For a plausible system of forces acting on a lower incisor, bodily retraction occurs when the force is applied labially, whereas a force applied lingually creates a tipping movement of the lower incisor that is accompanied by a greater loss of torque.

The intrusion of lower incisors is one of the most common movements in fixed appliance orthodontics. This is used, for example, during bite opening or for the flattening of the curve of Spee. The present FEM simulation demonstrates that lingual orthodontic appliances are more efficient than labial appliances for bodily intrusion of a lower incisor.

Conflict of interest

The authors have no conflicts of interest.

Riassunto

Obiettivi: Lo scopo di questo studio è di valutare le differenze meccaniche nell’applicazione di una forza ortodontica sulla superficie vestibolare o linguale di uno stesso dente. Lo studio è stato realizzato mediante un software di design CAD tridimensionale con il quale è stato creato un modello di un incisivo inferiore circondato dalla rappresentazione prismatica dell’osso mandibolare. Questo modello è stato soggetto a vari condizioni di carico con l’analisi a modelli finiti (FEM).

Materiali e metodi: Un’acquisizione mediante tomografia volumetrica è stata usata per creare un modello geometrico tridimensionale di un incisivo inferiore, insieme al suo legamento parodontale. Varie forze singole (orizzontali, verticali e laterali) e momenti (orizzontali e verticali; orizzontali, verticali e antiorari) sono stati applicati durante diverse simulazioni al centro della corona clinica della superficie vestibolare e linguale dell’ incisivo inferiore. Per valutare gli effetti delle varie forze considerate, sono stati considerati la dislocazione immediata e gli stress generati nell’osso e nel legamento parodontale.

Risultati: Il movimento dentale era influenzato dalla superficie di applicazione della forza solo quando erano presenti forze intrusive. Le simulazioni hanno evidenziato movimenti più grandi quando la forza verticale era applicata sul lato linguale. In genere, il movimento era di tipping quando erano applicate forze combinate, mentre c’era più intrusione in seguito all’applicazione di forze combinate e di un momento antiorario sulla superficie vestibolare.

Conclusioni: L’applicazione di una forza intrusiva su un incisivo inferiore sembra generare un movimento corporeo, mentre la stessa forza intrusiva applicata sulla superficie vestibolare determina tipping. Questo dovrebbe essere preso in considerazione ogni volta che viene fatto un piano di trattamento che prevede l’impiego di apparecchiature fisse.

Résumé

Objectifs: Le but de cette étude a été d’évaluer toutes les différences mécaniques entre l’application labiale et linguale d’une attache orthodontique par le biais d’une simulation virtuelle qui comprend une incisive inférieure entourée de son support osseux et soumise à de différentes conditions de charge.

Matériels et méthodes: L’imagerie par tomographie volumique à faisceau conique (CBCT) d’une incisive inférieure a été utilisée pour créer un premier modèle géométrique tridimensionnel et ensuite un modèle éléments finis de la dent, avec son support osseux et son ligament alvéo-dentaire. Des forces et des moments individuels (dans les sens horizontal, vertical et latéral) et combinés (sens horizontal et vertical; horizontal, vertical et antihoraire) ont été appliqués à ce modèle sur chaque côté de la dent au milieu de la couronne clinique.

Résultats: Dans le but d’évaluer l’effet des différentes forces prises en examen, le déplacement instantané dans le sens labiobuccal et le stress engendré sur l’os et le ligament parodontal, suite à ce mouvement, ont été mesurés et utilisés pour comparer les deux sites de mises en charge.

Conclusions: Le côté où la force a été appliquée n’a influencé le mouvement dentaire que lorsqu’une composante intrusive était présente. Par voie de conséquence, c’est le résultat souhaité qui devra déterminer le site de placement d’une attache. Les simulations réalisées ont mis en relief aussi un mouvement en corps supérieur lorsqu’une force verticale est présente sur la surface linguale. En général, ce mouvement a été du type oscillatoire lorsque des forces combinées ont été appliquées; toutefois, une intrusion en corps supérieur a été enregistrée après application de forces combinées et d’un moment de force antihoraire sur la surface labiale.

Resumen

Objetivo: El objetivo de este estudio es valorar cualquier diferencia mecánica entre la aplicación labial y lingual de un bracket ortodóntico, mediante la creación de un simulacro virtual que contempla un incisivo inferior rodeado de su soporte óseo, sometién-dolo a condiciones diferentes de carga.

Materiales y métodos: Realización de una imagen por tomografía de haz de cono (CBCT) en un incisivo inferior para crear, primero, un
modelo geométrico tridimensional y luego un modelo de elementos finitos del diente, completo con su soporte óseo y ligamento periodontal. Fuerzas y momentos individuales (horizontal, vertical y lateral) y combinados (horizontal y vertical, horizontal, sentido antihorario) han sido aplicados a este modelo, en ambos lados del diente, en el centro de la corona clínica.

Resultados: Para valorar el efecto de las diferentes fuerzas consideradas, fueron medidos tanto el desplazamiento instantáneo, en el sentido labiolingual, y el estrés engendrado en el hueso y el ligamento periodontal, a raíz de este movimiento. Lo anterior sirvió para comparar las dos soluciones a cargo.

Conclusiones: El lado en que se aplicó la fuerza influyó en el movimiento dentario únicamente cuando estaba presente un componente intrusivo. Por consiguiente, en estos casos, el lugar de colocación del bracket debería depender del resultado que se quiera lograr. Los simulacros realizados también destacaron un movimiento en cuerpo superior cuando estaba presente una fuerza vertical en la superficie lingual. En términos generales, este movimiento fue de tipo oscilatorio cuando se aplicaron fuerzas combinadas, pero se observó una intrusión en cuerpo superior en el caso de aplicación de fuerzas combinadas y un momento antihorario en la superficie labial.

REFERENCES