Effect of magnet position on tipping and bodily tooth movement in magnetic force-driven orthodontics

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Abstract

Magnets have many advantages for orthodontic applications. The purpose of this study was to investigate the effect of the magnet position on the tipping and bodily tooth movement using 3D digital analysis ex vivo.

Orthodontic typodont models for space-closing (2mm diastema) were created, mimicking maxillary central incisors. Tooth models (10mm crown and 14mm root length) created by 3D printer were used for the typodont model. Nd-Fe-B magnets were placed in the middle of the tooth (Model-M) and the cervical area (Model-C). The typodonts were immersed in a hot water-bath at 55°C to initiate tooth movement. The scanned typodont data before and after tooth movement were superimposed, and 3D coordinates (X, Y, Z) on the tooth were obtained. The root apex data was also obtained by superimposing the designed tooth model on the crown portion of the typodont model. 3D movement of the crown and the root apex, moving speed, degree of rotation (yaw, pitch, and roll) in 2 models were analyzed and compared by Pearson’s correlation confidents. Moderate crowding typodont cases were treated with two magnet position settings, and patterns of tooth/root movement and rotation were compared.

The largest movement was observed in the X-axis as intended. Model-M indicated higher moving speed and more tooth rotation than Model-C. In Model-M, the
root apex moved to the opposite direction of the crown movement with a negative
correlation. In contrast, the crown and root apex moved in the same direction with a
positive correlation in Model-C. In the ex vivo moderate crowding case, Model-C created
bodily movement, in which the cusp and root apex both moved in the same direction with
less tooth rotation.

The results of this study validated that modifying the position of the applied
magnetic force was able to increase the amount of bodily tooth movement and decrease
unwanted rotation/tipping in an ex vivo setting.

<Keywords>
Magnets, CAD/CAM, Superimposition, Orthodontics, typodont, 3D printer, 3D scanner
Introduction

Rare earth magnets, such as Sm-Co and Nd-Fe-B magnets were introduced in the 1970s and 1980s (1-3). Rare earth magnets have magnetic saturation, coercivity (resistance to demagnetization), and energy. These properties allowed for the production of small magnets. Nd-Fe-B magnets are less costly to produce than Sm-Co alloys, and are the most common rare earth permanent magnet in use today (3-6).

Magnets have many advantages for orthodontic applications (1, 4, 7, 8). Magnets does not decrease orthodontic force during tooth movement. Magnets can exert forces for tooth movement through physical barriers, such as mucosa and bone, and do not require patient compliance, as is the case with elastic bands. Oral hygiene may be performed more easily than with conventional fixed orthodontics with auxiliaries such as hooks, elastics, and spring coils. The magnetic force produced is inversely proportional to the square of the distance between them (1, 8-10). Magnets have been used in orthodontic treatment with limited approaches. The first report of the use of magnetic force to move teeth was in 1977 when Kawata and Takeda (11) described a technique of using magnetic brackets of Co-Cr-Fe alloy, bonded to the upper anterior and the lower anterior teeth, for the closure of interdental spaces (1, 3, 4). Prasad et al. reported that Nd-Fe-B magnets were used for diastema closure in a clinical study (4) and there are many other studies
and clinical reports using Nd-Fe-B magnets in orthodontic treatment, such as for forced eruption of impacted teeth (4, 5, 8, 10, 12-14). From an esthetic standpoint, magnets may not be ideal due to the black or metallic color. However, FeCo-(Al-fluoride) nanogranular films exhibiting ferromagnetic properties with high optical transparency in the visible light spectrum have been recently introduced (15).

The ultimate goal is the establishment of a magnetic force-driven orthodontics as a future treatment modality in comprehensive orthodontic care. The first analysis the efficacy of Nd-Fe-B magnetic attraction and repulsion forces by means of a three dimensional (3D) digital analysis of movement (distance, direction, angulation and duration) and rotation (yaw, pitch and roll) of the crown and root of teeth in an \textit{ex vivo} typodont model (16). We found that magnets are able to achieve desired tooth movements in a space-closing model, space-gain model and a moderate crowding case in an ex-vivo setting. However, more tipping movement and rotation were observed when using attractive forces. Bodily tooth movement more ideal that tipping tooth movement, as tipping may destructively influence the periodontal tissue in the cervical area (17). It was also shown that hyalinization occurs less frequently during bodily tooth movement than during tipping movements, because forces are more evenly distributed along the root surface during bodily movement (18). In this study, we hypothesized that the magnet
position can contribute to avoiding the occurrence of tipping movements. The purpose of
this study was to clarify the effect of the magnet position on the tipping and bodily tooth
movement by means of 3D digital analysis of tooth movement in X, Y and Z axis, and
rotation (yaw, pitch and roll) ex vivo.

Materials and Methods

1. Fabrication of typodont model with magnets and 3D digital scanning.

Dental typodonts mimicking maxillary central incisors were used in this ex vivo
experiment. Dental typodont models of maxillary central incisors (24 mm length, 10 mm
width, and 8.0 mm crown thickness) were designed using CAD software (Creo
Elements/Direct Modeling Express 4.0, PTC, Needham, MA, USA). Three 1.5 mm
diameter x 1.0 mm height cone-shaped measurement horns were created on the center of
the incisal edge, distal and lingual side of the tooth (Figure 1a). The designs were exported
as STL files. The tooth models were fabricated using a 3D printer (MiiCraft 125, MiiCraft
Inc., Hsinchu, Taiwan) using model resin (Next Dent Model 2.0, Next Dent BV,
Soesterberg, Netherland).

The typodont box (60 mm x 50 mm x 25 mm of outer frame, 30 mm x 30 mm x
20 mm of the inner tub) was designed using the CAD software. One hundred and twelve
landmarks (4.0 mm x 1.5 mm pentagonal cones) were created on the surfaces of the
typodont boxes (Figure 1b) in order to accurately superimpose data. Typodont boxes were fabricated in the same manner as the tooth models.

Ni-plated cylindrical Nd-Fe-B N52 magnets (NeoMag Co., Ltd., Chiba, Japan, 2.0 mm diameter x 5.0 mm, surface magnetic flux density 414 mT, adsorption power 22 kPa, density 7.5 g/cm³) were used in this *ex vivo* study. The magnets were bonded to the tooth with the north pole of the maxillary left central incisor (UL1) magnet facing the mesial and the south pole of the maxillary right central incisor (UR1) magnet facing the mesial, to produce attraction force, and the teeth were placed 2 mm apart. Two settings of magnet position were tested in this study. The magnet was placed in the middle of tooth crown (Model-M) and in the cervical area (Model-C, Figure 1b). The teeth were then stabilized in the typodont box using paraffin wax (Paraffin wax, GC Co., Ltd., Tokyo, Japan, solidification point 59.3°C). A plastic guide made with self-curing acrylic resin (Pattern Resin, GC Chicago, IL, USA) to standardize tooth position in each of 30 typodonts.

The typodonts were scanned using a 3D laser scanner (Ortho Insight 3D Laser Scanner, Motion View LLC., Chattanooga, TN, USA) prior to tooth movement. The typodonts were positioned in the center of the scanning table with the magnet facing forward. After the initial scan, the typodonts were divided into 10 groups, with 3
typodonts in each group for a total of 30 typodonts. The typodonts were immersed in a
digital thermostatic water bath (Joan Lab Digital Thermostatic Water Bath Manufacturer,
Ningbo Yinzhou Joan Lab Equipment Co., Ltd., Zhejiang, China, 3 L capacity) at 55°C to
initiate tooth movement from 5 min and up to 50 min in 5 min increments depending on
the group. After complete immersion of the typodont model in the water bath for the
prescribed time, the models were stabilized in a cold-water bath at 5°C for 30 min. After
stabilization the models were dried and scanned in the same manner as the initial scans.
The scanned typodont model data was converted into STL files using 3D
visualization software (Ortho Insight 3D, Motion View LLC., Chattanooga, TN, USA).
The pre-movement STL files were superimposed on the post-movement using 3D data
inspection software (GOM inspect, GOM, Braunschweig, Germany) using the 112
landmarks on the typodont box. 3D coordinates (X, Y, Z axis) of each of the 3
measurement points on the tooth model of UR1 and UL1 were obtained (Figure 2a). 3D
coordinates (X, Y, Z axis) of the center of root apex (CRA, Figure 2b) of UR1 and UL1
were obtained by superimposing designed tooth model on the crown portion of typodont
model.

2. Analysis of the movement and rotation of the tooth crown portion.
The center of gravity (CG) of each tooth crown was calculated using 3D
coordinates of 3 measurement points by the following equation (1).

\[ CG(x) = \frac{X_1 + X_2 + X_3}{3} \]
\[ CG(y) = \frac{Y_1 + Y_2 + Y_3}{3} \]
\[ CG(z) = \frac{Z_1 + Z_2 + Z_3}{3} \]  

The amount of 3D movement of the CG of each tooth crown portion (ACG) in each of 10 time-series was calculated by the following equation (2):

\[ ACG(X) = CG(X)_{post} - CG(X)_{pre} \]
\[ ACG(Y) = CG(Y)_{post} - CG(Y)_{pre} \]
\[ ACG(Z) = CG(Z)_{post} - CG(Z)_{pre} \]  

The speed of X-axis movement (mm/min) was calculated, using ACG by the following equation (3):

\[ \text{Speed (mm/min)} = \frac{ACG(t) - ACG(t-5)}{5} \]  

where \( ACG(t) \) is the amount of 3D movement of CG in the duration of \( t \) minutes. The average movement speed on Model-M and Model-C were compared.

Description of 3D rotation, yaw, pitch, and roll are shown in Figure 3. When given two cartesian coordinates, we can calculate the rotation using the dot and cross of the two vectors using equations (4, 5). The cross product will be used as the normal axis (n), and dot product will show the angle (\( \theta \)) of the rotation.

\[ n = a \times b \]  
\[ a \cdot b = \|a\|\|b\| \cos(\theta) \]
From the angle and the axis, it is possible to construct the rotation matrix \( R \) by using Rodrigues' rotation formula (19) below.

\[
R_\pi(\theta) = \begin{bmatrix}
\cos \theta + n_z^2(1 - \cos \theta) & n_x n_y(1 - \cos \theta) - n_z \sin \theta & n_x n_z(1 - \cos \theta) + n_y \sin \theta \\
\quad n_y n_x(1 - \cos \theta) + n_z \sin \theta & \cos \theta + n_z^2(1 - \cos \theta) & n_y n_z(1 - \cos \theta) - n_x \sin \theta \\
\quad n_z n_x(1 - \cos \theta) - n_y \sin \theta & n_z n_y(1 - \cos \theta) + n_x \sin \theta & \cos \theta + n_x^2(1 - \cos \theta)
\end{bmatrix}
\]

There are several ways to show the rotational transition, we use the yaw (Z-axis), pitch (X-axis), and roll (Y-axis) angles.

\[
\begin{bmatrix}
\cos \beta \cos \alpha & \sin \gamma \sin \beta \cos \alpha - \cos \gamma \sin \alpha & \sin \gamma \sin \alpha + \cos \gamma \sin \beta \cos \alpha \\
\cos \beta \sin \alpha & \sin \gamma \sin \beta \sin \alpha + \cos \gamma \cos \alpha & -\sin \gamma \cos \alpha + \cos \gamma \sin \beta \sin \alpha \\
\quad -\sin \beta & \sin \gamma \cos \beta & \cos \gamma \cos \beta
\end{bmatrix}
\]  

(7)

Given the rotation matrix (7), we can derive gamma, beta, alpha from the following equation (8):

\[
R_{31} = -\sin \beta
\]

\[
R_{32} = \sin \gamma \cos \beta
\]

\[
R_{33} = \cos \gamma \cos \beta
\]

3. Analysis of the movement of center of root apex.

Amount of 3D movement of the CRA of each root (ACRA) was calculated using 3D coordinates of CRA (Figure 2b) with the following equation (9):

\[
ACR(X) = CRA(X)_{\text{post}} - CRA(X)_{\text{pre}}
\]

\[
ACR(Y) = CRA(Y)_{\text{post}} - CRA(Y)_{\text{pre}}
\]

(9)
\[ ACR(Z) = CRA(Z)_{post} - CRA(Z)_{pre} \]

4. Application of the magnetic force-driven technique to the moderate crowding case.

A moderate crowding case including teeth maxillary right canine (UR3) to maxillary left canine (UL3) was created in the typodont model and the magnets were placed to setup both attraction and repulsion forces to straighten the arch form (Figure 4). The attraction magnet force was placed in 5 areas (UR4 mesial – UR3 distal, UR2 mesial – UR1 distal, UR1 mesial – UL1 mesial, UL1 distal – UL2 mesial, UL3 distal – UL4 mesial) and repulsion force was placed in 2 areas (UR3 mesial – UR2 distal and UL2 distal – UL3 mesial). A nickel-titanium archwire, 0.012 inch Sentalloy (TOMY INTERNATIONAL INC., Tokyo, Japan) was used as to guide the movement and establish the desired arch form. The model was scanned pre and post-movement and 3D movement and rotation were analyzed in the same manner.

5. Statistical analysis

Crown and root movement, crown speed, and crown rotation in each of 2 groups were obtained and averaged in each of 10 time-series and average data was used for the statistical analysis. Two-way ANOVA and Pearson’s correlation coefficient were used (p<0.01).

Results
1. **Crown movement**

Magnet position and duration were both significant factors in crown movement in all three axes (p<0.01) (Figure 5). Cervical placement of the magnet resulted in less movement, in the X and Z axes, with no difference in the Y axis. The largest movement in three dimensions was X-axis on both models, which was the intended movement. The amount of movement on the X-axis in 50 minutes on Model-M and Model-C at 1.01 mm and 0.64 mm, respectively.

2. **Speed**

Magnet position influenced the speed of movement, with the maximum rate of movement on Model-M and Model-C at 0.050 mm/min and 0.043 mm/min, respectively. The greatest movement speed was observed on the X-axis, which was the intended direction of movement (Figure 6).

3. **Tooth rotation**

Magnet position and duration were both significant factors on yaw and roll (Figure 7). The largest rotation was observed on yaw in both Model-M and Model-C at 3.22 degrees and 1.39 degrees, respectively, in 50 minutes (p<0.01). In the pitch, there were no significant differences between Model-M and Model-C. When considering roll, significantly greater rotation in Model-M was observed than in Model-C in 50 minutes.
(p<0.01), at 2.89 degrees and 0.67 degrees, respectively (p<0.01).

4. Relationship (Association) of tooth and root movement

Magnet position was a significant factor in the direction of root apex movement (Figure 8). In Model-M, ACR moved in the opposite direction to ACG, but in Model-C, ACG and ACR moved in the same direction. In Model-M, a weak negative correlation was observed between ACG and ACR on X-axis ($R=-0.29$) and a strong positive correlation was observed on Z-axis ($R=0.92$) (Figure 9a-c). In Model-C, a positive moderate correlation was found ($R=0.56$) on the X-axis, and a strong positive correlation was observed on Z-axis ($R=0.78$) (Figure 9d-f).

5. Application of the magnetic force-driven technique to the moderate crowding case.

In the moderate crowding case, different patterns were seen in crown and root apex movement based on the magnet position (Figure 10). In Model-M tipping movement was observed, in which the root apex moved in the opposite direction of the cusp. In contrast, in Model-C, bodily movement was observed, in which the cusp and root apex both moved distally. Less tooth rotation was observed in in Model-C compared to Model-M.

Discussion

Optimal orthodontic treatment requires a mechanical input that leads to a maximum rate of tooth movement with minimal irreversible damage to the root,
periodontal ligament, and alveolar bone (20). The level of optimal force for orthodontic
tooth movement is controversial and has not yet been defined (21), as it is a consequence
of multiple biological responses to orthodontic force. Higher forces do not always move
teeth faster than lower forces, but higher forces had more areas of hyalinization (22).

Recent studies have indicated that continuous forces result in faster tooth
movement than intermittent forces (23-25), but continuous forces caused greater root
resorption with a greater unwanted rotational movement. Root-resorption and alveolar
bone resorption are major biological damage observed by inappropriate orthodontics
applications (23-26). Unwanted rotational movement results in more root resorption in
the middle third level of the tooth (23). It can be summarized that the magnitude of
optimal force should be determined individually for each patient and intermittent force
should be applied to minimize unwanted outcomes by monitoring tooth movement
closely. Accurate force control is an essential factor.

Different types of loading force produce different types of tooth movement (27).
Cervical bone resorption and total alveolar bone thickness at mid-root and apical levels
were decreased with tipping movements compared to bodily movement (17, 28).
Different settings of auxiliary appliances can create the different movements, such as a
use of the sliding tube, round-wire or square-wire, and shapes of advancing loops (17,
In our previous study, attractive magnet force applied in the middle of maxillary central incisor for 2mm diastema closure in ex vivo model created the tipping movement (16). Tipping movement was identified by 3D digital assessment of movement and rotation of tooth and root apex. In this study, we assessed tooth and root apex movement and rotation with 2 different setting of the position of magnet placement, one at the middle of crown (Model-M) and the other in the cervical area (Model-C).

As we hypothesized, the position of the magnet was a significant factor for creating tipping or bodily movement. Bodily movement is produced with linear force, but tipping forces are produced with lever force with a fulcrum, which in the case of orthodontics is the level of the alveolar bone, or in the case of this study is the level of the paraffin wax. By moving the force more incisally, the distance of the lever force to the fulcrum increases, which for the same amount of force would produce a higher proportion of torque/rotation force along the fulcrum. By moving the force more apically, the opposite occurs, decreasing the amount of tipping force and increasing the linear force for bodily movement. This was confirmed with the 3D digital analysis which indicated that the Model-C created more bodily movement than Model-M, which had greater movement/speed due to the increased force output with a lever, but created more unwanted tipping/rotation. This result was same as the report by Lee et al. (29). The use
of greater magnet force at the cervical area can compensate for the decrease of tooth movement distance and speed while minimizing unwanted rotation. The *ex vivo* moderate crowding case validated that Model-C created bodily movement and less rotation on the canines with attracting force.

Placing orthodontic brackets in conventional fixed orthodontics at the cervical aspect of the tooth crown creates unwanted side effects due to the proximity to the gingival margin, with gingival enlargement/hyperplasia and gingivitis being the most common (30). This is likely due to a combination of difficult oral hygiene leading to plaque accumulation, as well as interactions between the metal from the brackets and the periodontium. Magnets could offer a significant advantage in this regard, with a much smaller profile without additional hooks or coiled springs allowing for oral hygiene and minimizing plaque accumulation.

The biggest limitation of this study is the use of a typodont model in an *ex vivo* setting. One drawback to the *ex vivo* environment is the lack of interaction of oral fluids on the magnet which may potentially create corrosion. However, new coatings have been developed to combat corrosion, such as nickel/alumina composite coatings and multilayer titanium nitride ceramic coatings, as well as the development of corrosion resistant magnets, such as iron-platinum (FePt) magnets (31). Tooth movement in vivo is also
much more complex and dynamic biological process than can be simulated in this
typodont model and further research is required to study the clinical environment.

Conclusion

The 3D data obtained in this study validated that modifying the position of the
applied magnetic force was able to increase the amount of bodily tooth movement and
decrease unwanted rotation/tipping in an ex vivo setting. Magnets were able to achieve
desired bodily tooth movements in a moderate crowding ex vivo model with an attractive
force.

List of abbreviations

3D Three dimensional
UL1 Maxillary left central incisor
UR1 Maxillary right central incisor
Model-A Model with the magnet placed in the middle of tooth crown
Model-C Model with the magnet placed in the cervical area
CRA Center of root apex
CG Center of gravity
ACG Amount of 3D movement of the center of gravity
ACR Amount of 3D movement of the center of root apex
Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and materials

The dataset used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests

Not applicable.

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Authors' contributions
Our study was carried out with collaboration of all authors. SIN conceived and designed the study. YI, YK and KO performed the experiments and analyzed the data. CL and JDD interpreted the results. YI, CL, JDD and SIN wrote the manuscript. All authors approved the final manuscript.

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Legends

Figure 1. Typodont model used in this study. (a) design and sizes of maxillary left central incisor (UL1), (b) scheme of typodont model.

Figure 2. Explanations of tooth movements and rotations. (a) X, Y and Z axis direction of tooth movement, (b) Identification of center or root apex.

Figure 3. Explanations of tooth rotations. (a) yaw, (b) pitch, (c) roll.

Figure 4. Typodont model of a moderate crowding case including teeth UL3-UR3. Canine is supposed to move distally by magnetic force-driven.

Figure 5. Average amount of movement on the center of gravity (ACG). (a) X-axis, (b) Y-axis, (c) Z-axis.

Figure 6. Average moving speed of the center of gravity.

Figure 7. Average amount of tooth rotation. (a) yaw, (b) pitch, (c) roll.

Figure 8. 3D graphs of amount of movement of the center of gravity of each tooth crown portion (ACG) and the center of root apex (ACR). (a) Model-M, (b) Model-C.
Figure 9. Average amount of 3D movement of the center of gravity of each tooth crown portion (ACG) and the center of root apex (ACR). (a) X-axis, (b) Y-axis, (c) Z-axis on Model-M, and (d) X-axis, (e) Y-axis, (f) Z-axis on Model-C.

Figure 10. Results of tooth movement by magnetic force-driven on typodont model of a moderate crowding case. (a) Images of UR3 and UL3 of pre- and post-movement, (b) distance moved on Crown and root apex, (c) mesial tooth rotation.