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

Yoshiki Ishida

Harvard School of Dental Medicine

Yukinori Kuwajima

Harvard School of Dental Medicine

Cliff Lee

University of California, San Francisco School of Dentistry

Kaho Ogawa

Harvard School of Dental Medicine

John Daren Da Silva

Harvard School of Dental Medicine

Shigemi Ishikawa-Nagai (✉ shigemi_nagai@hsdm.harvard.edu)

Harvard School of Dental Medicine

Research article

Keywords: Magnets, CAD/CAM, Superimposition, Orthodontics, typodont, 3D printer, 3D scanner

Posted Date: December 30th, 2019

DOI: <https://doi.org/10.21203/rs.2.19722/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Version of Record: A version of this preprint was published at Materials on August 13th, 2020. See the published version at <https://doi.org/10.3390/ma13163588>.

<Title>

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

<Authors>

Yoshiki Ishida¹, Yukinori Kuwajima¹, Cliff Lee², Kaho Ogawa¹, John D. Da Silva³,
Shigemi Ishikawa-Nagai¹

¹ Department of Oral Medicine, Immunity and Infection, Harvard School of Dental
Medicine, 188 Longwood Avenue, Boston, MA, United States

² Department of Orofacial Sciences, Division of Periodontology, University of California,
San Francisco School of Dentistry, 513 Parnassus Ave, San Francisco, CA, United States

³ Department of Restorative Dentistry and Biomaterial Sciences, Harvard School of
Dental Medicine, 188 Longwood Avenue, Boston, MA, United State

<Corresponding author>

Shigemi Ishikawa-Nagai, Yukinori Kuwajima

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 *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 than 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).

$$CG(x) = \frac{X_1+X_2+X_3}{3} \quad CG(y) = \frac{Y_1+Y_2+Y_3}{3} \quad CG(z) = \frac{Z_1+Z_2+Z_3}{3} \quad (1)$$

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):

$$ACG(X) = CG(X)_{post} - CG(X)_{pre}$$

$$ACG(Y) = CG(Y)_{post} - CG(Y)_{pre} \quad (2)$$

$$ACG(Z) = CG(Z)_{post} - CG(Z)_{pre}$$

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

$$Speed (mm/min) = \frac{ACG(t) - ACG(t-5)}{5} \quad (3)$$

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 (θ) of the rotation.

$$n = a \times b \quad (4)$$

$$a \cdot b = \|a\| \|b\| \cos(\theta) \quad (5)$$

163 From the angle and the axis, it is possible to construct the rotation matrix (R) by using
 164 Rodrigues' rotation formula (19) (6) below.

$$165 \quad R_n(\theta) =$$

$$166 \quad \begin{bmatrix} \cos \theta + n_x^2(1 - \cos \theta) & n_x n_y(1 - \cos \theta) - n_z \sin \theta & n_x n_z(1 - \cos \theta) + n_y \sin \theta \\ n_y n_x(1 - \cos \theta) + n_z \sin \theta & \cos \theta + n_y^2(1 - \cos \theta) & n_y n_z(1 - \cos \theta) - n_x \sin \theta \\ n_z n_x(1 - \cos \theta) - n_y \sin \theta & n_z n_y(1 - \cos \theta) + n_x \sin \theta & \cos \theta + n_z^2(1 - \cos \theta) \end{bmatrix}$$

167 (6)

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

$$170 \quad \begin{bmatrix} \cos \beta \cos \alpha & \sin \gamma \sin \beta \cos \alpha - \cos \gamma \sin \alpha & \sin \gamma \sin \alpha + \cos \gamma \sin \beta \cos \alpha \\ \cos \beta \sin \alpha & \sin \gamma \sin \beta \sin \alpha + \cos \gamma \cos \alpha & -\sin \gamma \cos \alpha + \cos \gamma \sin \beta \sin \alpha \\ -\sin \beta & \sin \gamma \cos \beta & \cos \gamma \cos \beta \end{bmatrix} \quad (7)$$

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

$$173 \quad R_{31} = -\sin \beta$$

$$174 \quad R_{32} = \sin \gamma \cos \beta \quad (8)$$

$$175 \quad R_{33} = \cos \gamma \cos \beta$$

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

177 Amount of 3D movement of the CRA of each root (ACRA) was calculated using
 178 3D coordinates of CRA (Figure 2b) with the following equation (9):

$$179 \quad ACR(X) = CRA(X)_{post} - CRA(X)_{pre}$$

$$180 \quad ACR(Y) = CRA(Y)_{post} - CRA(Y)_{pre} \quad (9)$$

$$ACR(Z) = CRA(Z)_{post} - CRA(Z)_{pre}$$

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 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,

28). 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

307 UL2 Maxillary left lateral incisor
308 UR2 Maxillary right lateral incisor
309 UL3 Maxillary left canine
310 UR3 Maxillary right canine
311 UL4 Maxillary left first premolar
312 UR4 Maxillary right first premolar

313 **Ethics approval and consent to participate**

314 Not applicable.

315 **Consent for publication**

316 Not applicable.

317 **Availability of data and materials**

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

320 **Competing interests**

321 Not applicable.

322 **Funding**

323 There was no funding support available for this research.

324 **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.

Acknowledgements

Not applicable.

References

1. Darendeliler MA, Darendeliler A, Mandurino M. Clinical application of magnets in orthodontics and biological implications: a review. *European journal of orthodontics*. 1997;19(4):431-42.
2. Robinson AL, Gschneidner K, Capellen JJ-THYoRE. Powerful new magnet material found. North-Holland Publishing Co., Amsterdam; 1987. p. 19.
3. Bhat VS, Shenoy KK, Premkumar PJAoM, Sciences H. Magnets in dentistry. 2013;1(1):73.
4. Prasad M, Manoj-Kumar M, Gowri-Sankar S, Chaitanya N, Vivek-Reddy G, Venkatesh N. Clinical evaluation of neodymium-iron-boron (Ne₂Fe₁₄B) rare earth magnets in the treatment of mid line diastemas. *Journal of clinical and experimental dentistry*. 2016;8(2):e164-71.

- 343 5. Hwang HS, Lee KH. Intrusion of overerupted molars by corticotomy and
344 magnets. American journal of orthodontics and dentofacial orthopedics : official
345 publication of the American Association of Orthodontists, its constituent societies, and
346 the American Board of Orthodontics. 2001;120(2):209-16.
- 347 6. Riley MA, Walmsley AD, Harris IR. Magnets in prosthetic dentistry. The Journal
348 of prosthetic dentistry. 2001;86(2):137-42.
- 349 7. Muller M. The use of magnets in orthodontics: an alternative means to produce
350 tooth movement. European journal of orthodontics. 1984;6(4):247-53.
- 351 8. Huang TTY, Elekdag-Turk S, Dalci O, Almuzian M, Karadeniz EI, Gonzales C,
352 et al. The extent of root resorption and tooth movement following the application of
353 ascending and descending magnetic forces: a prospective split mouth, microcomputed-
354 tomography study. European journal of orthodontics. 2017;39(5):547-53.
- 355 9. Mussard M, Le Mouél J-L, Poirier J-PJCRG. On some early attempts to
356 determine the variation of the magnetic force with distance. 2013;345(5-6):225-9.
- 357 10. Bondemark L, Kurol J, Hallonsten AL, Andreasen JO. Attractive magnets for
358 orthodontic extrusion of crown-root fractured teeth. American journal of orthodontics and
359 dentofacial orthopedics : official publication of the American Association of
360 Orthodontists, its constituent societies, and the American Board of Orthodontics.

361 1997;112(2):187-93.

362 11. Kawata T, Takeda S, editors. NEW ORTHODONTIC APPLIANCE BY MEANS
363 OF MAGNETIC BRACKET. Journal of Dental Research; 1977: AMER ASSOC
364 DENTAL RESEARCH 1619 DUKE ST, ALEXANDRIA, VA 22314.

365 12. Sandler JP. An attractive solution to unerupted teeth. American journal of
366 orthodontics and dentofacial orthopedics : official publication of the American
367 Association of Orthodontists, its constituent societies, and the American Board of
368 Orthodontics. 1991;100(6):489-93.

369 13. Phelan A, Tarraf NE, Taylor P, Honscheid R, Drescher D, Baccetti T, et al.
370 Skeletal and dental outcomes of a new magnetic functional appliance, the Sydney
371 Magnoglide, in Class II correction. American journal of orthodontics and dentofacial
372 orthopedics : official publication of the American Association of Orthodontists, its
373 constituent societies, and the American Board of Orthodontics. 2012;141(6):759-72.

374 14. Zhao N, Feng J, Hu Z, Chen R, Shen G. Effects of a novel magnetic orthopedic
375 appliance (MOA-III) on the dentofacial complex in mild to moderate skeletal class III
376 children. Head & face medicine. 2015;11:34.

377 15. Kobayashi N, Masumoto H, Takahashi S, Maekawa S. Optically Transparent
378 Ferromagnetic Nanogranular Films with Tunable Transmittance. Scientific reports.

379 2016;6:34227.

380 16. Kuwajima Y, Ishida Y, Lee C, Mayama H, Satoh K, Ishikawa-Nagai SJH. 3D
381 digital analysis of magnetic force-driven orthodontic tooth movement.
382 2019;5(11):e02861.

383 17. Kondo T, Hotokezaka H, Hamanaka R, Hashimoto M, Nakano-Tajima T, Arita
384 K, et al. Types of tooth movement, bodily or tipping, do not affect the displacement of the
385 tooth's center of resistance but do affect the alveolar bone resorption. The Angle
386 orthodontist. 2017;87(4):563-9.

387 18. Pilon JJ, Kuijpers-Jagtman AM, Maltha JC. Magnitude of orthodontic forces and
388 rate of bodily tooth movement. An experimental study. American journal of orthodontics
389 and dentofacial orthopedics : official publication of the American Association of
390 Orthodontists, its constituent societies, and the American Board of Orthodontics.
391 1996;110(1):16-23.

392 19. Olinde R. Des lois gometriques qui regissent les dplacements d'un systme solide
393 dans l'espace, et de la variation des coordonnes provenant de ces dplacement consideres
394 ind; pendent des causes qui peuvent les produire. J Math Pures Appl 1840;5:380-400.

395 20. Burstone CJJTbotm. The biophysics of bone remodeling during orthodontics
396 (optimal force considerations). 1989:321-33.

- 397 21. Ren Y, Maltha JC, Kuijpers-Jagtman AM. Optimum force magnitude for
398 orthodontic tooth movement: a systematic literature review. The Angle orthodontist.
399 2003;73(1):86-92.
- 400 22. Ren Y, Maltha JC, Van 't Hof MA, Kuijpers-Jagtman AM. Optimum force
401 magnitude for orthodontic tooth movement: a mathematic model. American journal of
402 orthodontics and dentofacial orthopedics : official publication of the American
403 Association of Orthodontists, its constituent societies, and the American Board of
404 Orthodontics. 2004;125(1):71-7.
- 405 23. Ozkalayci N, Karadeniz EI, Elekdag-Turk S, Turk T, Cheng LL, Darendeliler
406 MA. Effect of continuous versus intermittent orthodontic forces on root resorption: A
407 microcomputed tomography study. The Angle orthodontist. 2018;88(6):733-9.
- 408 24. Ballard DJ, Jones AS, Petocz P, Darendeliler MA. Physical properties of root
409 cementum: part 11. Continuous vs intermittent controlled orthodontic forces on root
410 resorption. A microcomputed-tomography study. American journal of orthodontics and
411 dentofacial orthopedics : official publication of the American Association of
412 Orthodontists, its constituent societies, and the American Board of Orthodontics.
413 2009;136(1):8.e1-8; discussion -9.
- 414 25. Maltha JC, van Leeuwen EJ, Dijkman GE, Kuijpers-Jagtman AM. Incidence and

- 415 severity of root resorption in orthodontically moved premolars in dogs. *Orthodontics &*
 416 *craniofacial research*. 2004;7(2):115-21.
- 417 26. Gay G, Ravera S, Castroflorio T, Garino F, Rossini G, Parrini S, et al. Root
 418 resorption during orthodontic treatment with Invisalign®: a radiometric study.
 419 2017;18(1):12.
- 420 27. Kusy RP, Tulloch JF. Analysis of moment/force ratios in the mechanics of tooth
 421 movement. *American journal of orthodontics and dentofacial orthopedics : official*
 422 *publication of the American Association of Orthodontists, its constituent societies, and*
 423 *the American Board of Orthodontics*. 1986;90(2):127-31.
- 424 28. Chaimongkol P, Thongudomporn U, Lindauer SJ. Alveolar bone response to
 425 light-force tipping and bodily movement in maxillary incisor advancement: A prospective
 426 randomized clinical trial. *The Angle orthodontist*. 2018;88(1):58-66.
- 427 29. Lee BW. The force requirements for tooth movement, Part I: Tipping and bodily
 428 movement. *Australian orthodontic journal*. 1995;13(4):238-48.
- 429 30. Gursoy UK, Sokucu O, Uitto VJ, Aydin A, Demirer S, Toker H, et al. The role of
 430 nickel accumulation and epithelial cell proliferation in orthodontic treatment-induced
 431 gingival overgrowth. *European journal of orthodontics*. 2007;29(6):555-8.
- 432 31. Yiu EY, Fang DT, Chu FC, Chow TW. Corrosion resistance of iron-platinum

magnets. Journal of dentistry. 2004;32(6):423-9.

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.

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

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

Figures

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 of 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.