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Research article

3D digital analysis of tooth movement with magnets and elastics in vitro

Yoshiki Ishida [a,b], Yukinori Kuwajima [a,c,*], Kaho Ogawa [a,c], Cliff Lee [a], John Da Silva [d], Jacob Emge [a,e], Shigemi Ishikawa-Nagai [a]

[a] Department of Oral Medicine, Immunity and Infection, Harvard School of Dental Medicine, 188 Longwood Avenue, Boston, MA 02115, United States
[b] Department of Dental Materials Science, School of Life Dentistry at Tokyo, The Nippon Dental University, 1-9-20 Fujimi, Chiyoda-ku, Tokyo 102-8159, Japan
[c] Division of Orthodontics, Department of Developmental Oral Health Science, School of Dentistry Iwate Medical University, 1-3-27 Chuo-dori, Morioka, Iwate 020-8505, Japan
[d] Department of Restorative Dentistry and Biomaterials Science, Harvard School of Dental Medicine, 188 Longwood Avenue, Boston, MA 02115, United States
[e] Department of Orofacial Sciences, University of California, Los Angeles, School of Dentistry, CA 90095, United States

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ABSTRACT

Objectives: Magnets have many advantages in orthodontics, and our previous studies confirmed their therapeutic potential through 3D-data analysis. The aim of this study was to compare tooth movements, including rotation, obtained via magnetic and elastic forces in crowded cases *in vitro*.
Methods: Typodont models mimicking a crowded case were prepared. In the magnetic force-driven orthodontics (MG) group, Nd-Fe-B magnets were attached to the labial surfaces from UR4 to UL4 for attracting force, and to UR6 and UL6 for repulsing force. For the elastic force-driven orthodontic (EL) group, brackets were placed on labial surfaces from UR2 to UL2 with power-chain elastics. A NiTi archwire was used in both groups. The models were 3D scanned before and after tooth movement and exported as STL files. The pre- and post-movement STL files were superimposed. The 3D coordinates of the measurement points of the crown and root apex were obtained, and tooth displacement, 3D movements (X, Y, and Z-axis), and rotation (yaw, pitch, and roll) were calculated. Two-tailed Student's t-test was performed for comparison of the results between MG and EL groups ($n = 3$).
Results: Overall, both groups indicated similar movement and rotation to achieve the planned arch form. In the crown movement and rotation, no significant differences were observed between MG and EL groups. However, in the root movement, there was a significant difference between MG and EL groups in X and Z axis for the canines.
Conclusions: Magnetic force-driven orthodontics demonstrated comparable results to elastics with less tipping movement, suggesting a potential future orthodontic modality.
Clinical significance: This *in vitro* study showed the potential of magnetic force for orthodontic application. The magnetic force-driven orthodontics might provide less tipping tooth movement compared to conventional methods, such as power chains, and could be a future technique for comprehensive orthodontic treatment.

1. Introduction

Magnets have a wide range of clinical applications in orthodontics. In addition to being utilized to generate movement, such as intrusion [1], extrusion [2, 3] or expansion [4], magnets are also applied in a variety of functional appliances [5]. This is because there are many advantages to the application of magnets over traditional orthodontic appliances. For example, conventional orthodontic appliances, including powerchains and elastics, generate a force that decreases over time. Magnets, by comparison, can provide a continuous force throughout treatment [6, 7, 8, 9]. In addition, it is possible t magnetic forces can be maintained through mucosa and bone. Since magnets generate a force that is inversely proportional to the square of the distance between them, the force can be predicted by measuring the distance between the magnets [8, 9, 10, 11, 12].

Magnetic forces have been utilized in orthodontics since the 1970s. The first report of the utilization of magnetic force to move teeth was designed by Kawata and Takeda in 1977 [13]. They explained an application of Co–Cr–Fe magnet brackets placed to the anterior teeth to close the interdental spaces [6, 9, 14]. Before this, their utilization was limited in orthodontics due to the lack of availability of small magnets [14] until the development of rare-earth magnets, for

* Corresponding author.
E-mail address: ykuwaji@iwate-med.ac.jp (Y. Kuwajima).

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instance, Sm–Co and Nd-Fe-B in the 1970s. These are valuable tools because unlike others, rare-earth magnets have high magnetic saturation, coercivity (resistance to demagnetization), and energy [9, 14, 15] even in small sizes. It is less expensive to produce Nd-Fe-B magnets than Sm–Co magnets. In addition, Nd-Fe-B magnets are the most widespread rare rare-earth magnet in use today [1, 6, 14, 16]. Nd-Fe-B magnets have been used in the oral cavity, as recognized by various studies and clinical case reports [1, 2, 5, 6, 8, 12, 17]. However, the 3D movement and rotations of teeth by magnetic force have not been fully elucidated.

Our previous studies using 3D analysis validated the use of magnetic-force-driven orthodontics, using attraction and repulsion forces in an *ex vivo* setting [18]. It was demonstrated that bigger movements occurred by attraction force over repulsion force, generating a greater maximum speed within 50 min of the force application. The attraction force also created other undesirable movements, including rotation and tipping, phenomena not observed in the model with the repulsion force [19]. We also reported that investigation of the effect of the magnet position on the tipping and bodily tooth movement in an *ex vivo* setting [19]. It was demonstrated that increasing the amount of bodily tooth movement and decreasing undesirable tooth rotation and tipping could occur by modifying the position of the magnets. However, the study had limitations due to the use of typodont models which included only two teeth. Further studies using clinical case-mimicking typodont models are necessary to assess magnetic force driven orthodontic treatment compared to the conventional orthodontic appliances.

Elastics have been commonly used in orthodontic treatment. Qodcieh *et al.* concluded that 50% of elastic-force degradation occurred in the first four to 5 h of placement [20]. Several other studies also reported the large initial decrease in the force generated by elastics in orthodontics treatment [20, 21, 22, 23, 24, 25], potentially requiring the orthodontist to change a treatment plan to include higher forces than deemed necessary [23]. To reconcile this dilemma, one study suggested that patients be instructed to change elastics twice daily to minimize relaxation [24]. Others have suggested that elastics that generate a higher force than needed be used and that these elastics should be pre-stretched before use to prevent higher forces in the first few hours of application [25]. Another confounding factor of elastic use are oral activities (i.e. chewing, speaking, etc.) and variation in oral environments (i.e. temperature, pH balance, etc.). However, elastics still occupy a major role in orthodontic treatment.

Because magnets generate forces that are both easy to calculate and are not impacted by confounding factors nor a degradation of elasticity, magnets could be an alternative modality in orthodontics. Therefore, it is important to know whether the magnetic force can create the same orthodontic results as those generated by elastic force. This study aimed to examine the possibility of magnets replacing elastics in orthodontic treatment by comparing the tooth movement between magnets and elastics. We hypothesized that magnetic force can generate tooth movement similar to that of elastic force.

2. Materials and methods

2.1. Preparation of experimental typodont model

Tooth models of anterior teeth were designed using Meshmixer CAD software (Autodesk, San Rafael, CA, USA), Figure 1A. The typodont frame was also designed using the same CAD software (Figure 1B). The designs of both the tooth models and the typodont frame were exported as STL files and, a digital-light-processing 3D printer (MiiCraft 125, MiiCraft, Hsinchu, Taiwan) with 3D printing material (Next Dent Model 2.0, Next Dent BV, Soesterberg, Netherland) were used to fabricate the models. A moderate crowding case with maxillary right canine to maxillary left canine was placed using paraffin wax (Paraffin wax, GC, Tokyo, Japan, solidification point 59.3 °C) in the typodont model for this *ex vivo* experiment (Figure 1C).

2.2. Tooth movement by magnets and elastics

Orthodontic setting for the magnetic force-driven orthodontic group (MG group) and the elastic force-driven orthodontic group (EL group) are shown in Figure 2.

For MG group, a 0.012-inch Ni–Ti archwire (Sentalloy, TOMY INTERNATIONAL, Tokyo, Japan) was applied to manage the tooth movement and create the ideal arch form. The Ni-plated cylindrical Nd-Fe-B magnets (N52, NeoMag, Chiba, Japan, 2.0 mm diameter x 5.0 mm length, surface magnetic flux density 0.41 T, adsorption power 22.0 kPa, density 7.5 g/cm^3) were attached to create magnetic force using autopolymerizing acrylic resin (Pattern Resin, GC, Tokyo, Japan) (Figure 2A). Attraction force was set on UR4 to UL4, and repulsing forces was set on UR6 and UL6. UR1 and UL1 were stabilized by two magnets attached (Figure 2B).

For EL group, brackets (Aria Low-Profile Brackets, Ortho Dentaurum, Tokyo, Japan) were placed on all tooth surfaces with powerchain elastics (Prochain medium force M space, Dentsply Sirona, Tokyo, Japan) and a 0.016 × .022-inch Ni–Ti archwire was applied from UR6 to UL6 (Figure 2C). The orthodontic settings were performed by the same experienced orthodontist.

Before tooth movement, 3D scanning of the typodont models was performed using a desktop 3D scanner (Ortho Insight 3D, Motion View, Chattanooga, TN, USA). Then, for tooth movement initiation in the typodont models, the models were immersed at 55 °C for 30 min in a 3.0-litter thermostatic water bath (BHS-1, Ningbo Yinzhou Joan Lab Equipment, Zhejiang, China). After finishing immersing for 30 min, the models were placed in an iced-water at 5 °C for 30 min to stabilize the tooth movement. After stabilization, the models were dried and then scanned in the same way as the scans performed before tooth movement.

2.3. 3D analysis of the tooth movement and rotation

The scanned data of the typodont model was loaded to 3D software (Ortho Insight 3D Scan software, Motion View, Chattanooga, TN, USA)

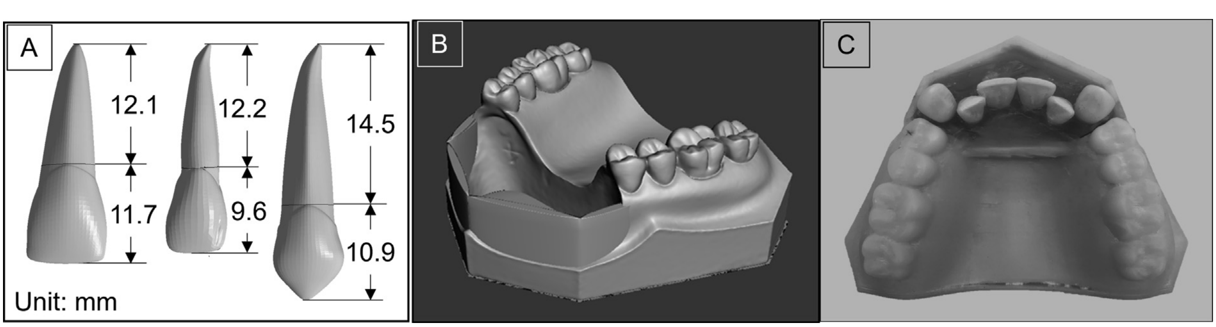

Figure 1. Typodont model used in this study. (A) tooth models, (B) typodont, (C) crowding case used.

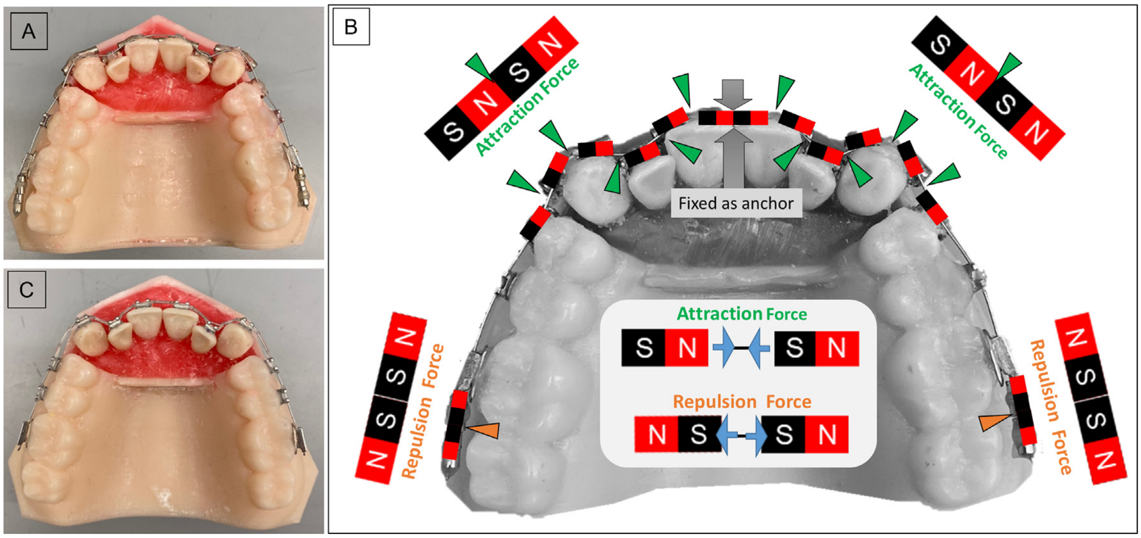

Figure 2. Orthodontics force setting on crowding typodont model. (A) Magnets force setting on the typodont, (B) Blue map of magnets setting, (C) Elastic force setting.

and converted into STL files. Superimposition of the pre-movement STL files on that of the post-movement was performed using 3D data analysis software (GOM inspect 2019, GOM, Braunschweig, Germany) with a best-fit algorithm. The 3D coordinates of the middle of the incisal edge (measurement point-I) and root apex (measurement point-R) on the tooth models were obtained (Figure 3A).

The amount of movement of the tooth crown (AC, measurement point-I, Figure 3A) in the X, Y and Z-axis was calculated using the following Eq. (1).

$$AC\ (X) = I\ (X)_{Post} - I\ (X)_{Pre}$$

$$AC\ (Y) = I\ (Y)_{Post} - I\ (Y)_{Pre} \tag{1}$$

$$AC\ (Z) = I\ (Z)_{Post} - I\ (Z)_{Pre}$$

The amount of movement of the root apex (AR, measurement point-R, Figure 3A) in the X, Y and Z axes was calculated using the following Eq. (2).

$$AR\ (X) = R\ (X)_{Post} - R\ (X)_{Pre}$$

$$AR\ (Y) = R(Y)_{Post} - R\ (Y)_{Pre} \tag{2}$$

$$AR\ (Z) = R\ (Z)_{Post} - R\ (Z)_{Pre}$$

For the calculations of 3D rotation, yaw, pitch, and roll (Figure 3B), the same method from our previous published study [18, 19] was used.

2.3.1. Color displacement map

A color displacement map was used by 3D data inspection software to quantify the tooth movement and direction before and after tooth-movement. The average displacement of each tooth was calculated and the difference between MG group and EL group was compared.

2.3.2. Statistical analysis

All experiments were repeated three times ($n = 3$) by the same trained examiners. For statistical processing of the results of crown-and-root

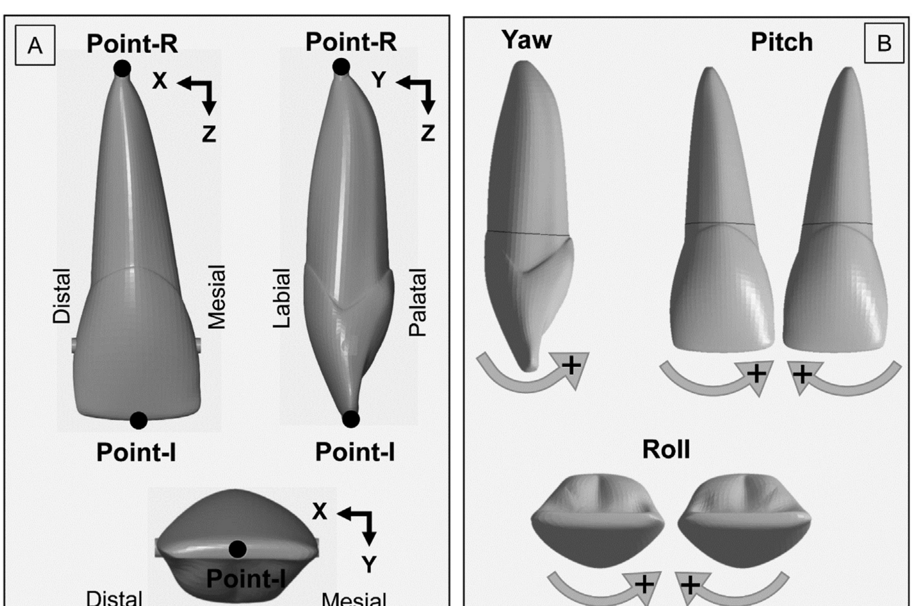

Figure 3. Measurement points and direction on tooth crown and root. (A) Movement on X, Y and Z axis. (B) Rotation, Yaw, Pitch and Roll.

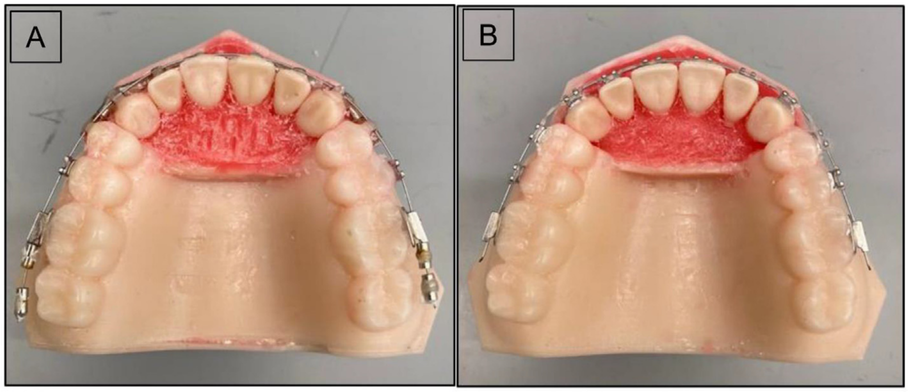

Figure 4. Post-movement typodont models. (A) Magnetic force-driven group, (B) Elastic force-driven group.

movement and crown rotation, two-tailed Student's t-test was used ($\alpha = 0.05$, SPSS ver. 24, IBM, Armonk, NY, USA).

3. Results

3.1. Overview of typodont models of both MG and EL groups

After immersing for 30 min in a hot water bath, tooth movements occurred, and the crowding arch was aligned in both MG group and EL group (Figure 4).

3.2. Displacement in color map

Color displacement map showed that lateral incisors were predominantly in the orange-red range on labial view and in the light-blue range on palatal view indicating movement toward labial in both MG group and EL group. In contrast, canines indicated movement toward lingual (Figure 5). The central incisors were fixed as anchors and color displacement was not observed. The average crown displacement of lateral incisors was 0.60 ± 0.38 mm for EL group and 0.54 ± 0.16 mm for MG group. The average of canines was 0.47 ± 0.14 mm and 0.49 ± 0.11 mm, respectively. The average root displacement of lateral incisors was 0.09 ± 0.07 mm for EL group and 0.11 ± 0.09 mm for MG group, 0.18 ± 0.14 mm and 0.37 ± 0.16 mm on canines, respectively. There was no significant difference between MG group and EL group.

3.3. Moving distance of the crown and root in X, Y and Z-axis

The distance traveled by the crown and root in the X, Y, and Z-axis are shown in Table 1 and Figure 6. The lateral incisors-crown moved markedly to the labial direction to the correct position in the arch as expected. No significant difference was observed between MG group and EL group in all directions ($p > 0.05$). For the canines, the distal and palatal movements were observed in both MG group and EL group. In the MG group, significant intrusion of 0.722 mm along the axial plane was observed over the EL group ($p < 0.01$).

For the lateral incisor roots, a slight mesial movement (X-axis, 0.2–0.4 mm), palatal movement (Y-axis, 1.0–1.4 mm), and extrusion (Z-axis, 0.87–0.99 mm) were observed for both MG group and EL group. No significant difference was found between MG group and EL group ($p > 0.05$). For the canine roots, MG group had little mesial movement while EL group indicated significantly larger movement (X-axis, 0.7 mm, $p < 0.05$). MG group indicated significantly larger intrusion (Y-axis, 0.9mm) than EL group ($p < 0.05$).

For the central incisors, both MG and EL group indicated only slight movement of the crown (-0.044–0.159) and root (-0.15–0.085), and there was no significant difference between MG and EL group.

3.4. Tooth rotation

The tooth rotations calculated using the 3D coordinates of the crown portion are shown in Table 1. A labial inclination and mesial inclination

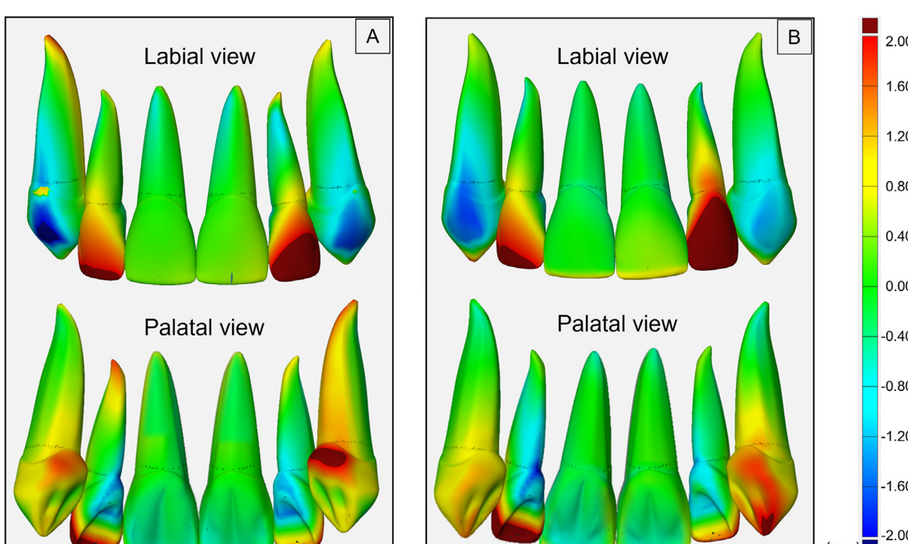

Figure 5. The color displacement map between pre- and post-tooth movement. A: Magnetic force-driven group, B: Elastic force-driven group. The green (zero point) indicates no displacement. The red indicates the outward displacement. The blue indicates the inward displacement.

Table 1. Amount of movement on X, Y and Z axis, and degree of rotation, Yaw, Pitch and Roll.

	X axis			Y axis			Z axis		
CROWN	Magnet	Elastic	STAT	Magnet	Elastic	STAT	Magnet	Elastic	STAT
Lateral Incisor	0.178 ± 0.140	0.119 ± 0.464	*NS*	-2.921 ± 0.329	-3.09 ± 0.863	*NS*	0.123 ± 0.266	0.282 ± 0.244	*NS*
Canine	0.775 ± 0.139	0.978 ± 0.129	*NS*	2.233 ± 0.239	1.944 ± 0.372	*NS*	-0.722 ± 0.406	0.111 ± 0.302	*
ROOT	Magnet	Elastic		Magnet	Elastic		Magnet	Elastic	
Lateral Incisor	-0.205 ± 0.483	-0.456 ± 0.351	*NS*	1.431 ± 0.222	1.075 ± 0.291	*NS*	0.786 ± 0.474	0.977 ± 0.457	*NS*
Canine	-0.199 ± 0.286	-0.747 ± 0.366	*	0.054 ± 0.351	-0.567 ± 0.265	*NS*	-0.933 ± 0.386	-0.285 ± 0.257	*
Rotation	Yaw			Pitch			Roll		
	Magnet	Elastic	STAT	Magnet	Elastic	STAT	Magnet	Elastic	STAT
Lateral Incisor	-11.820 ± 1.718	-12.018 ± 3.572	*NS*	4.887 ± 3.367	8.640 ± 4.223	*NS*	0.830 ± 0.814	1.634 ± 1.132	*NS*
Canine	4.474 ± 1.14	5.387 ± 1.115	*NS*	-6.014 ± 2.323	-6.426 ± 4.069	*NS*	1.055 ± 0.789	1.062 ± 0.477	*NS*

* indicates significant differences between the magnet and elastic groups ($p < 0.05$).

were observed in the lateral incisors, while opposite inclinations were observed in the canines. No significant difference was observed between MG group and EL group in all rotation parameters ($p > 0.05$).

For the central incisors, there was no significant difference between MG and EL group on Yaw, Pitch and Roll.

4. Discussion

In order for tooth movement to occur in orthodontic treatment, an adequate magnitude of force is necessary for initiation of a local inflammatory response, allowing for remodeling of the structure supporting the tooth, including the alveolar bone [26]. The level of ideal force for tooth movement in orthodontic treatment is controversial and has not yet been fully elucidated [27], as it is a consequence of multiple biological responses to orthodontic force. While small and intermittent force are not enough for tooth movement, excessive great force might cause root resorption, an undesired result [28, 29, 30]. Therefore, it is important to predict the appropriate orthodontic force needed to avoid applying excessive force while concurrently providing adequate force.

In the conventional fixed appliances, a loss of orthodontic force must be considered because of the friction between brackets and wires as well as that between appliances and teeth. Thus, it is difficult to calculate the ideal orthodontic force one should apply to a given patient's dentition. In addition, it has been a common finding that elastics lose their initial ability to apply force once they are placed in the mouth and exposed to an environment that provides both mechanical and chemical strain [25]. However, even with modern technologies, it is currently impossible to accurately calculate the decline of initial force elicited by elastics due to the inability of clinicians to predict these variables.

In contrast, the force applied by separated magnets increases inversely to the second power of the distance as a consequence of the force–distance relationship being hyperbolic [8, 9, 10, 12]. Thus, the magnitude of force can be calculated by measuring the distance between magnets. In this study, we have used an archwire to manage the orthodontic movement and to create the ideal arch form in MG group in the same way as EL group. The wire also played a critical task in guiding the direction of magnetic force.

Magnets, especially rare earth magnets, do not show any material fatigue, which often occurs with elastics in conventional orthodontic mechanics [12]. However, it is said that rare-earth magnets might get corroded easily in the oral cavity. Saliva causes corrosion and a loss of magnetic force [1, 14, 16, 31], but coating rare-earth magnets with stainless steel or titanium can prevent this [16, 31]. Recently, a new coating techniques have been produced, such as those involving Ni–Al composite and multilayer titanium nitride ceramic. In addition, some magnets, such as Fe–Pt magnets, are tolerant to said corrosion [32].

In our previous *ex vivo* study, attractive magnets generated a force that, when applied to the center of the maxillary central incisor to close 2 mm of interdental space, caused them tipping movements [18]. Moreover, in our other study, we assessed crown and root apex movement and rotation with two different settings of the magnet position, one at the center of the crown and the other in the cervical area [19]. Our present 3D data analysis on the comparison of the tooth movement between magnetic force-driven and conventional

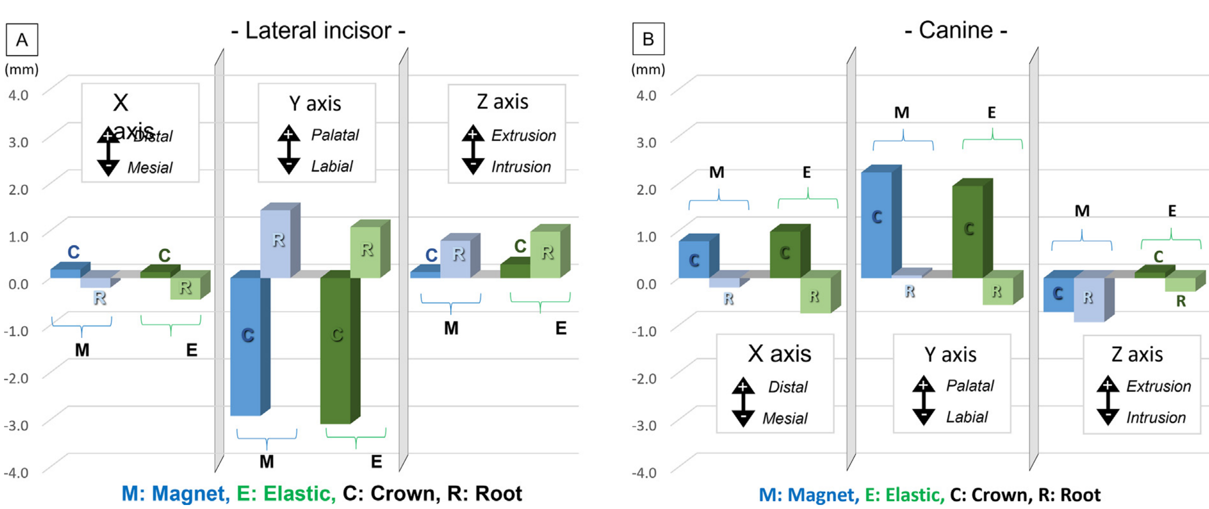

Figure 6. Comparison of 3D movement and direction of tooth crown and root by magnet and elastic orthodontic force. A: Lateral incisor. B: Canine.

elastics provided valuable information for the upcoming advancement of magnetic force-driven orthodontics. There were no significant differences between MG group and EL group in the crown movement and rotation except the movement of the tooth in an axial direction. The height of the attached appliances might cause a difference in the tooth axial direction. In the movement of the root apex of the canines, the EL group moved significantly more mesially than the MG group despite the distal movement of the crowns. This indicates that canines of the EL group moved in a tipping-like movement whereas the MG group had bodily movement. Our results suggested that the tooth movement of magnetic force-driven could minimize unwanted incidents of tipping. In addition, the utilization of magnets, as opposed to elastics, limits the issue of patient compliance since magnets do not need to be replaced regularly.

The use of a typodont model in an *ex vivo* study is the limitation of this study. One problem to the *ex vivo* situation is the lack of interaction of oral fluids on the magnet, which may cause corrosion. Besides, tooth movement *in vivo* is much more complicated due to the dynamic nature of the oral cavity and periodontium, and paraffin wax cannot adequately simulate the biology. Despite the limitations, this study is the first to look at a potential of magnetic-force driven orthodontics compared to the elastic force-driven orthodontic for the case of moderate crowding in *ex vivo* using 3D digital analysis. Our results will lead further investigations to apply the use of magnets *in vivo*.

5. Conclusion

There were no significant differences in the translational movement of the crowns and root apices, and tooth rotation between the magnetic force-driven treatment and those with the elastics. In addition, magnetic force-driven treatment may prevent unwanted tipping and root movements. Magnetic force-driven orthodontics may be a future technique for comprehensive orthodontic treatment.

Declarations

Author contribution statement

Yoshiki Ishida, John Da Silva, Jacob Emge: Analyzed and interpreted the data; Wrote the paper.

Yukinori Kuwajima, Kaho Ogawa: Conceived and designed the experiments; Performed the experiments; Contributed reagents, materials, analysis tools or data.

Cliff Lee: Contributed reagents, materials, analysis tools or data; Wrote the paper.

Shigemi Ishikawa-Nagai: Conceived and designed the experiments; Wrote the paper.

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Data availability statement

Data will be made available on request.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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