sciendo
DOI: 10.2478/aoj-2012-0013

The force-distance properties of attracting magnetic attachments for tooth movement in combination with clear sequential aligners

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Background: The demand for clear sequential aligner therapy has increased dramatically in recent years. An improved system utilising small neodymium-iron-boron (NdFeB) magnetic attachments has been proposed to enhance appliance capabilities.
Aim: The aim of the investigation was to analyse the force system diagrams produced by small attracting NdFeB magnets to determine, 1) whether the force levels were sufficient to induce tooth movement, 2) the effect of magnet morphology on force characteristics and, 3) the most appropriate magnet dimensions that could be utilised for this application.
Methods: Twenty-nine NdFeB rectangular magnets of varying dimensions were tested. A Mach-1 universal testing machine (Biosyntech Inc, Quebec, Canada) was used to measure the attractive force of pairs of magnets. Measurements commenced with a magnetic pair in contact and subsequently vertically separated a distance of 10 mm at a speed of 12 mm/minute. For all magnetic configurations four repeat measurements were performed on five magnetic pairs of the same size.
Results: The force-distance diagrams for all magnet configurations demonstrated a dramatic decrease in force with increasing magnet separation. Rather than a suggested inverse square law, the experimental data followed an inverse fourth law when an offset determined by a regression analysis was applied to the distance. For the majority of magnets, insignificant forces were attained beyond 2 mm of separation. Magnets with large pole face areas and longer magnetic axes provided the greatest force.
Conclusions: A select range of magnet configurations exhibited suitable and reliable attractive forces and therefore could be advocated for prescribed clinical application.
(Aust Orthod J 2012; 28: 159–169)

Received for publication: March 2012
Accepted: October 2012

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Introduction

The demand for aesthetic orthodontic appliances has increased dramatically in recent years. Consequently, clear sequential aligner therapy has become a popular alternative to fixed appliances. Clear aligner therapy refers to a sequence of clear thermoplastic appliances made on a series of casts with reset teeth, each incorporating small corrective tooth movements.[1] These appliances, which are marketed as practically 'invisible', are considered to be more aesthetically appealing, but despite this, clear aligners are less effective than fixed appliance therapy.[2] Aligners are effective in tooth tipping but have limited effectiveness with other types of movements such as bodily movement, rotations, extrusions and severe intrusion of teeth.[1,3,4]

In an attempt to overcome the movement limitations of aligners, resin attachments may be bonded to selected teeth.[5,6] These attachments increase dental undercuts and retention and therefore facilitate appliance purchase to achieve desired tooth movements.[5] The selection of the appropriate attachment size and shape is influenced by several factors related to dental morphology, the role of the attachment and

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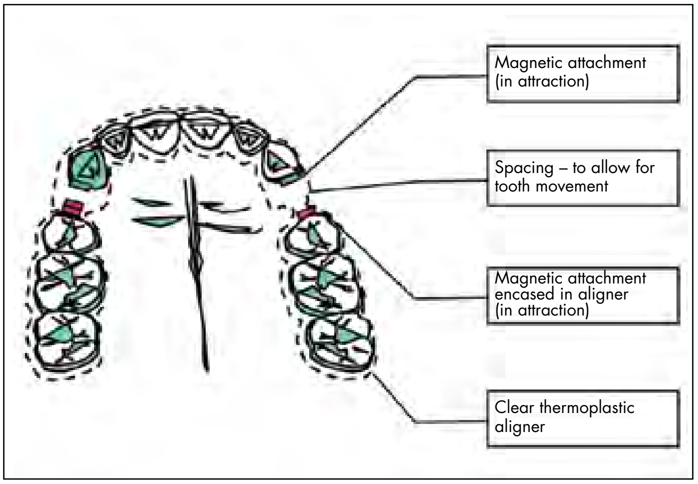


Figure 1. Schematic diagrammatic of the use of neodymium iron boron magnetic attachments for tooth movement in combination with clear sequential aligners.

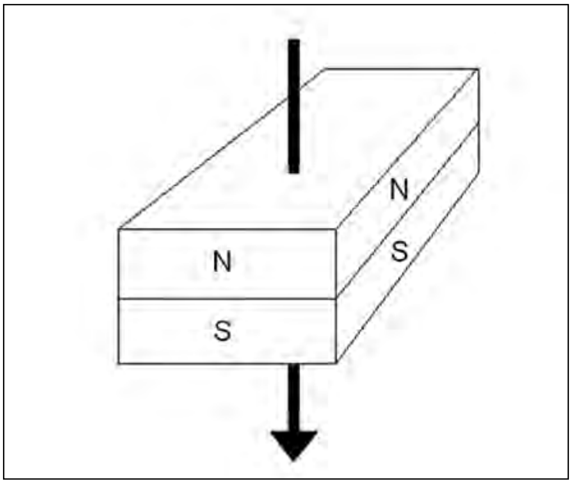


Figure 2. Magnet indicating direction of magnetisation and polarity of magnets used in this investigation.

the desired tooth movement.[5] Unfortunately, the use of attachments has been shown to only be partially effective.[4,6] Given the inherent limitations of clear appliances, they cannot be used routinely in severely crowded cases or as effectively in extraction cases.[7,8]

A system utilising small neodymium-iron-boron (NdFeB) magnetic attachments has been proposed to enhance the capabilities of clear aligners. In this system, a sequential aligning appliance is combined with at least one magnetic attachment positioned in an attractive or repulsive configuration and bonded to the surface of a tooth. A second magnet is encased in the thermoplastic material in the body of the appliance (Figure 1). NdFeB rare earth magnets are reported to provide the highest energy per unit volume of any commercially-available magnetic material.[9] Therefore the use of these magnetic attachments has the potential to create a force interaction that may theoretically make the movement of teeth, in any direction, possible and easier.

Magnetic forces have been used in orthodontics for tooth movement and orthopaedic correction with varying degrees of success.[10] Magnets have several advantages over traditional force delivery systems including a lack of friction, no material fatigue and the ability to produce predictable force levels over long periods of time.[9,10] However, the physical properties of magnets dictate that the attractive force reduces dramatically as the distance between the magnets increases.[11]

The present study aimed to examine the physical properties of attracting NdFeB magnets, used as attachments, to facilitate tooth movement in combination with clear sequential aligners. Specifically, the investigation was to analyse force system diagrams produced by small attracting NdFeB magnets to determine:

1. If the force levels were sufficient to induce tooth movement.
2. The effect of different magnet morphology on force characteristics.
3. The most appropriate dimensions of magnets that could be utilised.

Methods

NdFeB magnets

The magnets were fabricated from a neodymium-iron-boron alloy and were coated with nickel and copper (AMF Magnetics, Sydney, Australia). Commercially-available NdFeB permanent magnets are produced by a powder metallurgy process and are magnetised throughout their thickness (Figure 2).

A range of rectangular magnets of varying dimensions was selected, based on average tooth crown dimensions and the size of conventional rectangular resin attachments used by the Invisalign® system (Align Technology Inc, Santa Clara, CA, USA).[5,12] The dimensions of rectangular Invisalign® attachments vary in height (3, 4 and 5 mm), width (2 mm) and

Table I. The morphology of magnets used in this investigation.

Dimensions (mm)	Thickness				
	0.5	0.75	1	1.25	2
Width x length	1 x 4	0.75 x 5	0.75 x 4	0.75 x 3	3 x 3
	2 x 2	1 x 4	1 x 4	1 x 3	4 x 4
	2 x 3	1 x 5	1.5 x 4	1.5 x 3	
	2 x 4	1.5 x 5	2 x 3		
	2 x 5	2 x 2	2 x 4		
	3 x 3	2 x 3	3 x 3		
	3 x 4	2 x 4	3 x 4		
		2 x 5			
		3 x 3			
		3 x 4			

prominence (0.5 or 1 mm).[5] Twenty-nine different rectangular magnet dimensions were tested (Table I).

Apparatus

A Mach-1universal testing machine employing a 10 kg load cell (Biosyntech Inc, Quebec, Canada) was used to measure the attractive force of pairs of magnets. The lower component of the testing machine was immobile, while the upper component was attached to an electric motor that moved vertically. A customised non-magnetic mounting jig was constructed using aluminium (Figure 3). The base magnet was fixed with adhesive to an aluminium tab which screwed into the inferior component of the jig. The opposing magnet was placed, parallel and above, the base magnet. A small amount of adhesive (Loctite® Super Glue Gel Control™, Henkel, Düsseldorf, Germany) secured the superior magnet to its aluminium tab and the mobile upper jig component which was lowered until magnet to magnet contact was achieved. After five minutes, the upper component was raised to separate the magnetic pair and to confirm adherence. The load cell was calibrated at maximum separation of the equipment.

Measurement commenced with the magnetic pair in contact, following which the magnets were vertically separated to a distance of 10 mm at a speed of 12 mm/minute. There were no standardised instructions available for fixing the force-displacement curves of magnetic attachments (e.g. International Organisation for Standardisation [ISO] norms), consequently the measurement parameters were chosen with reference to previous studies.[13-16] The start position (0 µm) was determined as the position corresponding to the peak tensile force, otherwise known as the 'breakaway' load.[14] Force measurements at varying degrees of separation were recorded in grams and the results recorded electronically. Each measurement was repeated 4 times for every magnetic pair and 5 magnetic pairs were tested for every size. Therefore a total of 20 measurements was generated for each magnet size tested.

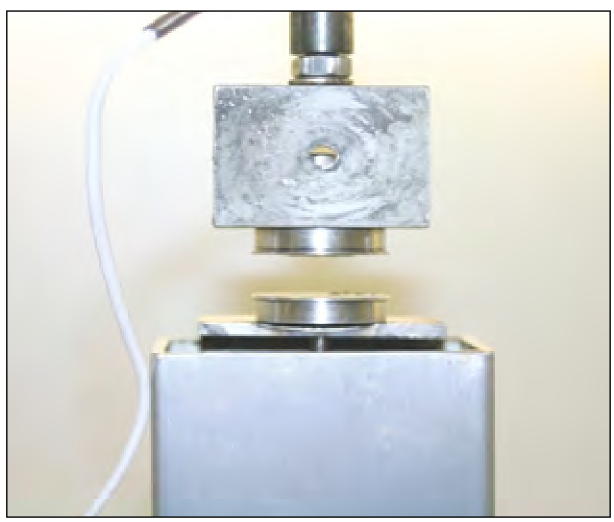


Figure 3. Mach-1 universal testing machine with customised mounting jig.

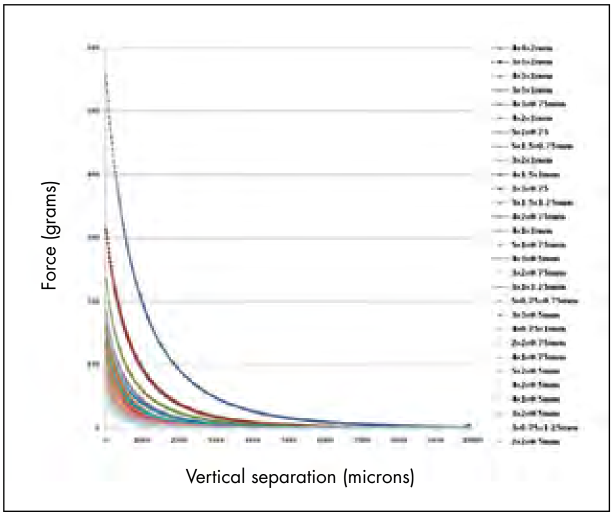


Figure 4. Force-displacement diagrams of the all tested NdFeB magnet configurations.

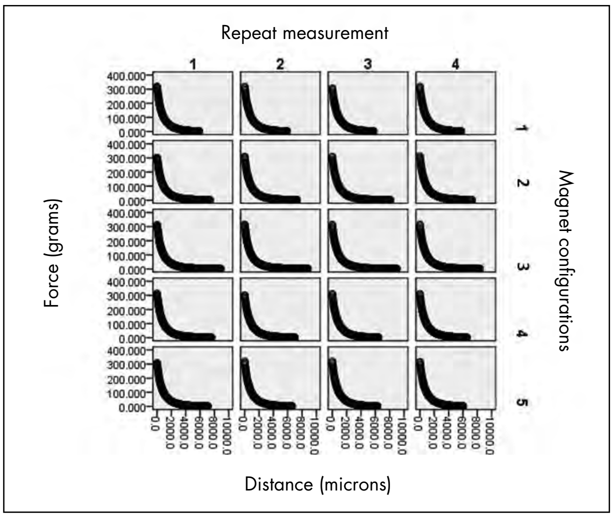


Figure 5. The force-distance diagrams of the 3 x 3 x 2 mm magnet demonstrating the outcomes for repeat measurements of the five magnetic pairs tested.

Table II. Results for the tested magnets with varying morphology.

			Clinically relevant force range	
Dimensions (l x w x h)	Maximum force (grams)	Activation range (microns)	Separation at MINIMUM force 15 g (microns)	Separation at MAXIMUM force 200 g (microns)
4 x 4 x 2	555.16	4181	5171	990
3 x 3 x 2	312.71	2924	3252	328
4 x 3 x 1	235.14	2542	2625	83
3 x 3 x 1	186.92	2072	2072	-
4 x 3 x 0.75	168.14	2020	2020	-
4 x 2 x 1	155.65	1575	1575	-
5 x 2 x 0.75	143.86	1458	1458	-
5 x 1.5 x 0.75	141.45	1285	1285	-
3 x 2 x 1	134.81	1440	1440	-
4 x 1.5 x 1	133.25	1257	1257	-
3 x 3 x 0.75	128.67	1558	1558	-
3 x 1.5 x 1.25	124.14	1315	1315	-
4 x 2 x 0.75	114.82	1218	1218	-
4 x 1 x 1	112.54	969	969	-
5 x 1 x 0.75	107.44	826	826	-
4 x 3 x 0.5	93.96	1127	1127	-
3 x 2 x 0.75	93.19	1066	1066	-
3 x 1 x 1.25	91.26	852	852	-
5 x 0.75 x 0.75	85.90	623	623	-
3 x 3 x 0.5	82.11	988	988	-
4 x 0.75 x 1	74.95	575	575	-
2 x 2 x 0.75	74.43	806	806	-
4 x 1 x 0.75	72.60	594	594	-
5 x 2 x 0.5	67.10	719	719	-
4 x 2 x 0.5	61.99	667	667	-
4 x 1 x 0.5	63.41	497	497	-
3 x 2 x 0.5	60.98	673	673	-
3 x 0.75 x 1.25	56.02	498	498	-
2 x 2 x 0.5	44.10	433	433	-

Measurement error

The presented force-displacement diagrams were constructed from the average of 20 measurements. One-way analysis of variance (ANOVA) for repeated measurements was performed on seven randomly selected magnet sizes. Both intra-magnet and inter-magnet measurement errors were analysed using the Statistical Package for Social Sciences (SPSS for Windows, version 16.0, Chicago, IL, USA).

Results

The average force-displacement diagrams of the 29 magnet configurations measured in the present investigation are depicted in Figure 4. All measurements indicated that the force decreased with increasing magnet separation. High forces were generated at small degrees of separation. The highest peak force of 555 g was produced by the 4 x 4 x 2 mm magnet, followed by the 3 x 3 x 2 mm magnet which produced a peak force of 312 grams. The lowest peak force of 44 g was generated by the 2 x 2 x 0.5 mm magnet (Table II).

Figure 5 demonstrates the force-distance diagrams generated for repeat measurements of one magnet

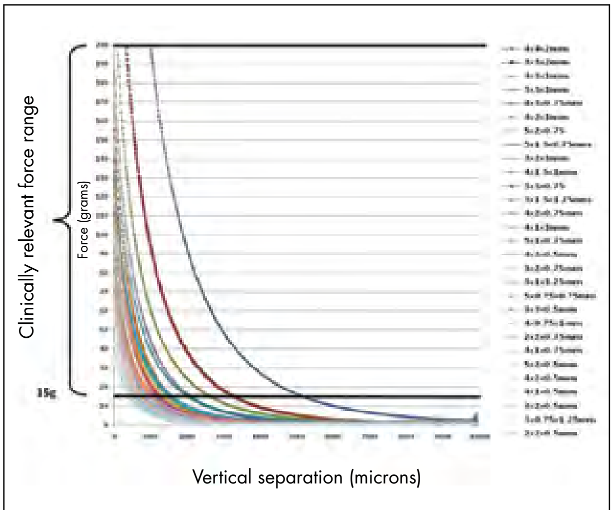


Figure 6. Force-displacement diagrams of the tested NdFeB magnet configurations indicating the clinically relevant force range.

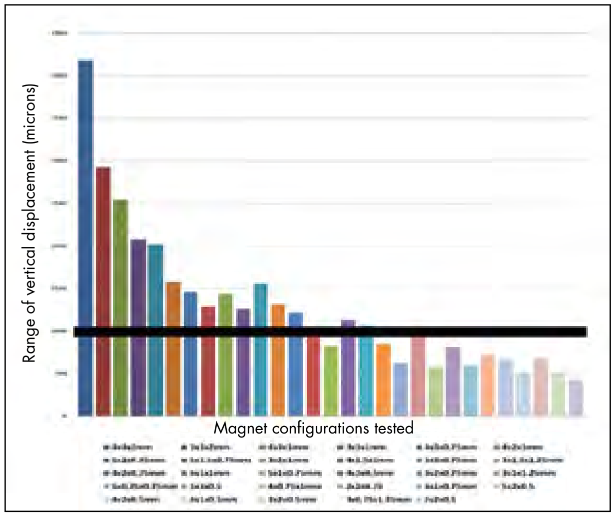


Figure 7. The activation range of each magnet configuration tested. The activation range refers to the range of vertical displacement in microns through which clinically relevant forces of 15-200 grams are generated.

Table III. Analysis of Variance of Repeat Measurements.

		One-way analysis of variance					
		Intra-magnet error			Inter-magnet error		
Magnet dimensions (mm)	Mean	Mean square error	Standard Deviation	% error	Mean square error	Standard Deviation	% error
3 x 3 x 2	312.72	23.53	4.85	1.55	52.41	7.24	2.32
3 x 3 x 1	186.92	12.51	3.54	1.89	307.04	17.52	9.37
2 x 2 x 0.5	44.10	1.88	1.37	3.10	6.35	2.52	5.72
5 x 1 x 0.75	107.44	1.86	1.36	1.27	63.95	7.99	7.44
4 x 2 x 1	155.65	7.42	2.73	1.75	16.84	4.10	2.64
4 x 1.5 x 1	133.25	5.66	2.38	1.79	16.93	4.12	3.09
4 x 4 x 2	555.16	13.67	3.70	0.67	377.76	19.44	3.50

configuration (3 x 3 x 2 mm). For all magnetic configurations, four repeat measurements were performed on five magnetic pairs of the same size. The variance of repeat measurements of an individual magnetic pair ranged from 0.67 - 3.1% of the mean value, while the variance between different magnetic pairs of the same size ranged from 2.32 - 9.37% of the mean value (Table III).

A range of 15-200 grams was chosen to represent clinically relevant force levels associated with tooth movement.[17] Figure 6 illustrates force-displacement curves for the tested magnet configurations and all, except for the three largest, generated peak force within the selected range. The larger magnet configurations of 4 x 4 x 2 mm, 3 x 3 x 2 mm and 4 x 3 x 1 mm, generated a maximum clinical force of 200 g at a vertical separation of 990 µm, 328 µm and 83 µm respectively. The majority of the magnets generated the minimum clinically significant force of 15 g at approximately 2 mm of separation or less. The three largest magnet configurations reached the minimum clinical force of 15 g at a vertical separation of 5171 µm, 3252 µm and 2625 µm respectively. Three magnet configurations, 3 x 0.75 x 1.25 mm, 4 x 1 x 0.5 mm and 2 x 2 x 0.5 mm, reached the minimum force of 15 g at 0.5 mm separation (Table II).

The range of vertical displacement over which clinically relevant forces were generated varied for all magnet configurations. The vertical displacement in microns through which clinically relevant forces

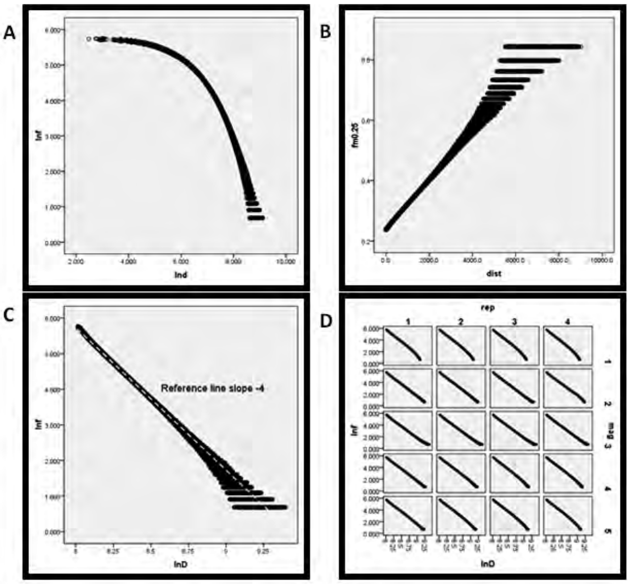


Figure 8. Functional relationship between force and displacement.

A. An exemplary plot of the logarithm of magnetic force against the logarithm of magnetic separation.
B. Standard plot of the logarithm of the inverse fourth root of the force (fm-0.25) against distance demonstrating an approximate linear relationship.
C. Typical plot of the log (force) against the log D (D = distance plus offset) follows a power law with coefficient of -4.
D. Typical plot of the log (force) against the log (distance plus offset) for individual measurements. The results of the 3 x 3 x 2 mm magnet are presented as an example of the typical outcomes.

were generated was deemed to be the activation range for each tested magnet (Table II). A comparison was conducted between the magnet configurations by noting the range of vertical displacement at which the desired force levels were reached (15-200 g, Figure 7). The 4 x 4 x 2 mm magnet had the greatest range of activation and the 2 x 2 x 0.5 mm magnet had the lowest range.

The relationship between force and magnet separation was evaluated by plotting the logarithm of magnetic force against the logarithm of distance. A typical log-log plot is shown in Figure 8A. A distinct curvature was evident in the log-log plot suggesting that the data did not obey the classic inverse square law. By applying a systematic data transformation approach to the results of this study, the inverse fourth root of the force ($fm^{-0.25}$) against distance was found to approximate a linear relationship (Figure 8B). The addition of an offset, obtained by fitting a linear regression of the transformed force variable ($fm^{-0.25}$) against distance (A/B), to the distance, suggested that force versus distance plus offset, follows an inverse fourth power law. Figure 8C demonstrates that the relationship for the log (force) against the log D (distance plus offset) follows a power law with a coefficient of -4. Figure 8D indicates that the relationship was consistent for repeat measurements of individual magnet configurations. The results of the 3 x 3 x 2 mm magnet are presented as an example of the typical outcomes (Figure 8).

Table IV summarises the offset values from the regression analysis for all magnetic configurations and the slope of the resulting plot of log force against log distance plus horizontal offset (D). The results were generally consistent and indicated an inverse fourth power law at small separations of 2 mm or less. The correlations between the offset and magnet dimensions – length (l), width (w), height (h), lw, lh or wh were analysed. The combination of height and cross-sectional area (lw) was highly significant ($p < 0.001$) and exhibited a correlation coefficient of 0.91. The regression on height alone was insignificant with a correlation coefficient of 0.44.

Discussion

The present laboratory-based study examined the force-displacement characteristics of attracting NdFeB magnets to assess if the force levels generated were sufficient to induce tooth movement. Most clinical strategies are based on the assumption that a force magnitude or a range of forces exist that, when applied to the periodontium, will yield an optimal rate of tooth movement.[1,18] The major factor that affects tooth movement is not force magnitude but the distribution of stress generated in the periodontium.[18-21] However, it is difficult to measure stresses and strains within the periodontal ligament and therefore force magnitudes have received significant attention in orthodontics.[19]

In the present investigation, a range of 15-200 grams was chosen to represent a clinically relevant force range. This force range was selected, based on previous investigations of the physical characteristics of magnets used for orthodontic tooth movement.[15,17] Mancini et al.[17] applied a clinically relevant force range of 15-200 g in an investigation of the physical characteristics of NdFeB magnets, whereas von Fraunhofer[15] and co-workers analysed samarium-cobalt magnets over an orthodontic force range of 75-150 grams. However, for comparative purposes, the larger force range of Mancini et al. was selected for this project.[17]

The larger magnet configurations 4 x 4 x 2 mm, 3 x 3 x 2 mm and 4 x 3 x 1 mm generated forces above the clinically accepted force range. High

Table IV. Summary of offset values from linear regression analysis for all magnetic configurations tested.

Magnet dimensions	A	B	Offset (A/B)	Slope	Standard error	Power value
4 x 4 x 2	0.21	0.000057	3667	-4.00	0.002	2.0
3 x 3 x 2	0.24	0.000083	2871	-3.98	0.002	2.0
4 x 3 x 1	0.26	0.000096	2719	-3.94	0.004	2.0
3 x 3 x 1	0.27	0.000116	2353	-4.01	0.003	2.0
4 x 3 x 0.75	0.29	0.000111	2568	-3.90	0.005	2.0
4 x 2 x 1	0.28	0.000157	1796	-4.24	0.014	2.0
5 x 2 x 0.75	0.29	0.000156	1853	-3.98	0.011	2.0
5 x 1.5 x 0.75	0.29	0.000179	1615	-4.08	0.010	2.0
3 x 2 x 1	0.29	0.000150	1960	-3.95	0.008	2.0
4 x 1.5 x 1	0.29	0.000173	1702	-4.04	0.010	2.0
3 x 3 x 0.75	0.30	0.000136	2197	-3.97	0.005	2.0
3 x 1.5 x 1.25	0.30	0.000162	1846	-3.97	0.008	2.0
4 x 2 x 0.75	0.31	0.000173	1763	-3.93	0.026	2.0
4 x 1 x 1	0.31	0.000207	1488	-3.83	0.013	2.0
5 x 1 x 0.75	0.31	0.000252	1224	-4.11	0.018	2.0
4 x 3 x 0.5	0.32	0.000169	1905	-3.94	0.013	2.0
3 x 2 x 0.75	0.32	0.000180	1783	-3.96	0.013	2.0
3 x 1 x 1.25	0.32	0.000220	1473	-3.93	0.007	2.0
5 x 0.75 x 0.75	0.33	0.000287	1143	-3.82	0.020	2.0
3 x 3 x 0.5	0.33	0.000171	1953	-3.82	0.011	2.0
4 x 0.75 x 1	0.34	0.000289	1176	-3.78	0.022	2.0
2 x 2 x 0.75	0.34	0.000222	1529	-4.02	0.016	2.0
4 x 1 x 0.75	0.34	0.000266	1179	-4.02	0.017	2.0
5 x 2 x 0.5	0.35	0.000218	1610	-3.88	0.011	2.0
4 x 2 x 0.5	0.36	0.000230	1552	-3.94	0.017	2.0
4 x 1 x 0.5	0.35	0.000334	1054	-4.13	0.017	2.0
3 x 2 x 0.5	0.36	0.000219	1642	-3.88	0.014	2.0
3 x 0.75 x 1.25	0.36	0.000288	1264	-3.93	0.014	2.0
2 x 2 x 0.5	0.39	0.000273	1422	-3.95	0.012	2.0

orthodontic forces are considered to be harmful due to the risk of high bone stress, root resorption, soft tissue dehiscences or loss of supporting bone.[16,22-24] Therefore, to avoid potential complications, the pole distance of these magnets would need to be clinically monitored.

The force-distance diagrams for all magnet configurations demonstrated a dramatic decrease in force with increasing magnet separation. This could equally be stated as an increasing force gradient as separation decreased, which is clinically applicable with the use of attractive magnets. Burstone[21] suggested that it might be biologically preferable to use an increasing gradient appliance. The rationale was that, as the periodontal ligament widened following orthodontic tooth movement, increasing forces might be required, as tooth mobility and vascularity had increased.

Table V. Dimensions of the magnets with the most clinically useful force characteristics and range.

Dimensions (mm)	Thickness		
	0.5	0.75	1
Width x length	3 x 4	1.5 x 5	1.5 x 4
		2 x 3	2 x 3
		2 x 5	2 x 4
		2 x 4	3 x 3
		3 x 3	
		3 x 4	

A range of magnets of varying configurations was examined. According to Vardimon et al.,[11] the performance of a magnetic system may be enhanced by increasing the length of the magnet which extends its magnetic axis. Alternatively, increasing the width of a magnet extends the pole surface area. The main factor in determining the maximum attractive force is the length of the magnetic axis representing the distance between the two magnetic poles. Increasing the width of the magnet affects the slope of the force-distance curve.[11] The present results support the conclusion that the largest pole face area and magnetic axis length generated the highest forces.

The inverse square law was not found to apply to the present experimental data. According to Coulomb's law, the force produced by any two magnets is inversely proportional to the square of the distance between them.[11,16,17,25,26] Although mention has been made of the application of the inverse square law in the dental literature,[11,16,17,25,26] many authors presented curves without comment on the functional relationship,[13,27,28] or reported that the law only 'approximately' applied.[16,25] Confusing alternate relationships have been previously documented, reporting that magnetic force, 'initially decreases as the square of the distance and subsequently, as the cube of the distance'[26] and an 'inverse square-root' relationship applied at small distances.[15]

The present study determined that an inverse fourth law operated when an offset was applied to the separation distance. The offset was obtained by fitting a linear regression of the transformed force variable (fm-0.25) against distance. The finding of a non-inverse square force-distance law is consistent with the results of Darvell and Dias[14,29] who found that an inverse square law did not apply for long thin magnets. Data demonstrated that the expected force-distance relationship approached an inverse fourth power law.[14,29] The rationale of Darvell and Dias considered that the commonly used elementary view of a simple dipole magnet was of little value in understanding the force-distance relationship at small distances.[14] It had previously been assumed that the surface of a magnet provided the appropriate reference plane for measuring distance and the variation in force was a simple distance function.[9,14] However, there is no known evidence which indicates that the functional pole resides at the magnet face.[14]

An offset, obtained by fitting a linear regression to the data, was added to the distance in order for the inverse fourth law relationship to apply. The offset adjusted the distance for differences in the physical size of the magnets and it was found that the offset increased with increasing height and cross-sectional area of the magnets ($p < 0.001$; correlation coefficient 0.91). Considering the offset was dependent on the physical characteristics of the magnet, as Darvell and Dias[14] suggested, it may represent the deviation of the apparent pole position from the end of the magnets.

Thermoplastic appliances can achieve 0.25 - 0.5 mm of tooth movement per aligner, therefore the proposed magnetic attachments must deliver clinically useful forces over this range to be of benefit.[1,5,30] The clinical use of magnets requires the application of a coating material applied to attach the magnet to the tooth surface and to prevent corrosion.[31,32] Therefore, the active range of a magnetic attachment should be greater than 1000 μm to account for the thickness of the coating material and the amount of tooth movement achievable by current thermoplastic appliances. It was intended that new magnetic attachments would be no larger than currently-used and commercially-available rectangular resin attachments. Based on the above criteria, eleven magnet configurations were deemed suitable for use as magnetic attachments in combination with clear sequential aligners (Table V).

The difference in force between individual magnet pairs was found to range from 2.32 – 9.37%. This compares favourably with the results of Bondmark and Kurol[16] who indicated a similar level of variation for repelling samarium-cobalt magnets. A variation of 6-9% was considered low and therefore the magnets

(a) (b)

Figure 9. Clinical example.
(a) Initial oral view. (b) Initial root angulation of central incisors.

(a) (b) (c)

Figure 10. Start of treatment.
(a) Magnetic attachments placed inter-proximally initially. (b) 0.8mm clear thermoplastic appliances with space for the desired tooth movement. (c) A stainless steel wire (016") was bonded to the lingual surfaces of the 13, 12, and 11 to prevent movement of these teeth, as the facial midline was coincident with the mesial surface of the 11.

could be routinely used without measuring the force of an individual pair.[16] Given that a similar variation was found in the present investigation, the conclusion of Bondmark and Kurol was supported.

The present study measured the force-displacement characteristics of a range of magnets in the vertical dimension with the magnet surfaces parallel to each other. If the magnets were applied clinically as attachments in combination with clear sequential aligners, it is unlikely that such conditions would be replicated and the magnets could be displaced in all three planes of space. Mancini et al.[17] found that horizontal displacements and angulations significantly reduced the pole face overlap, which directly affected the magnetic flux density and direction and therefore the force of attraction. Since both forces and moments work in all three planes, the effective force system acting on a tooth should be represented in three-dimensions.[33] While 3D forces and moments generated by magnetic devices have been previously measured,[11,33,34] a recommendation for future research is the characterisation of the three-dimensional force-displacement and moment-displacement diagrams of the most ideal magnetic attachments identified in the present investigation.

Clinical example

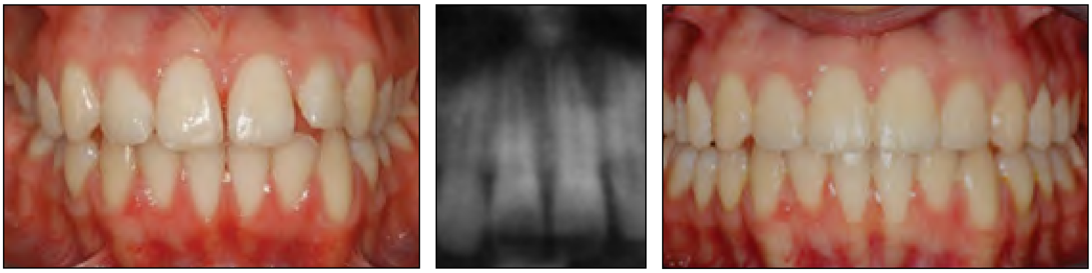
The following clinical example demonstrates the potential for magnetic attachments to expand the capabilities of clear sequential aligner therapy. A patient presented with a 5 mm diastema due to a broken upper fixed retainer which had debonded from tooth 22 (Figure 9). A desire to avoid retreatment with conventional fixed appliances was expressed.

NdFeB magnetic attachments (5 x 1.5 x 0.75 mm) were bonded indirectly to the central incisors using a conventional acid-etch technique. The magnetic attachments were initially placed on the mesial surfaces of the central incisors and then on the buccal surface as the space reduced. The magnets were plated with nickel and copper and coated with composite resin to provide an impermeable barrier. The barrier was designed to prevent ionic diffusion which would lead to corrosion, as well as facilitate the attachment of magnets to the teeth.[35]

A magnetic force was generated over a 3.72 mm range and reached a maximum of 141 grams. The theoretical maximum force was not reached as the resin coating material prevented full contact of the magnets. The patient was provided with 0.8 mm clear thermoplastic

(a) (b) (c)

Figure 11. Treatment progress.
(a) Three weeks in treatment. (b) Eight weeks in treatment. (c) Twelve weeks in treatment.



(a) (b) (c)

Figure 12. Treatment completion.
(a) Phase 1 diastema closed in 15 weeks. (b) Minimal tipping of central incisors. (c) Final oral view phase 2 with Invisalign treatment completed in 23 upper aligners and 28 lower aligners.

appliances (Erkodur, Erkodent®, Pfalzgrafenweiler, Germany) which incorporated space for the desired tooth movement (Figure 10). The patient was advised to wear the appliance full time except when oral hygiene was undertaken.

The objective of the initial phase of treatment using clear thermoplastic appliances in combination with magnetic attachments was confined to reduction of the diastema which closed in 15 weeks with minimal tooth tipping (Figures 11 and 12). Additional conventional sequential aligner therapy was directed at closing small residual spaces and achieving ideal alignment of the anterior teeth. This phase of treatment was completed using 23 upper aligners and 28 lower aligners (Figure 12c).

Conclusions

Based on the results of the present study the following conclusions may be drawn:

1. The neodymium-iron-boron magnet configurations examined displayed varying levels of clinical usefulness.
2. Magnet morphology affected clinical properties and performance.
3. A select range of magnet configurations exhibited suitable and reliable attractive forces and therefore could be advocated for clinical application as magnetic attachments in combination with clear sequential aligners.

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