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An *in vitro* study into the efficacy of complex tooth alignment with conventional and self-ligating brackets

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Structured Abstract

Objective – To evaluate the efficacy of tooth alignment achieved by various small cross-section archwire/bracket combinations using the orthodontic measurement and simulation system.

Materials and Methods – The study comprised three types of orthodontic brackets 1) conventional ligating (Victory Series and Mini-Taurus), 2) self-ligating (SmartClip a passive self-ligating bracket and Time3 an active self-ligating bracket), and 3) a conventional low-friction bracket (Synergy). All brackets had a nominal 0.022″ slot size. Brackets were combined with 1) 0.012″ stainless steel, 2) 0.012″ Orthonol, 3) 0.012″ Thermalloy, and 4) 0.0155″ coaxial archwires. Archwires were tied to the conventional brackets with stainless steel ligatures and elastomeric rings. The malocclusion simulated represented a central upper incisor displaced 2 mm gingivally (*x*-axis) and 2 mm labially (*z*-axis).

Results – The inciso-gingival correction achieved by the different archwire/bracket combinations ranged from 15 to 95%, while the labio-lingual correction ranged from 10 to 95%. The smallest correction was achieved by coaxial, Orthonol, and thermally archwires when ligated with the elastomeric rings to conventional brackets. Stainless steel archwires achieved from 65 to 90% of inciso-gingival correction and from 60 to 90% of labio-lingual correction.

Conclusion – The resultant tooth alignment was the product of interaction between the archwire type, bracket type, and bracket design including ligature type. Small cross-sectional archwires might produce up to 95% correction if combined properly with the bracket system. Elastomeric rings when used with conventional brackets limit the efficacy of malalignment correction.

Key words: orthodontic archwires; orthodontic brackets; tooth alignment

Introduction

Efficiency of orthodontic treatment is a major consideration, and different indicators of efficiency have been used in research including the speed of ligation and chairside time (1), the time required to complete alignment of a certain crowding (2), duration of orthodontic treatment or the number of visits required (3,4). The importance of treatment efficiency arises from the fact that treatment duration is a concern for many orthodontic patients who want to know for how long they will wear the braces as well as for clinicians who want to ensure efficient office management (5,6). Therefore, efficiency of orthodontic mechanics has been in the focus of orthodontic developments. Self-ligating brackets have been developed to overcome the disadvantages of conventional ligation. Self-ligation was thought to be better than conventional ligation regarding ergonomics, deformation, discoloration, plaque accumulation, friction, and efficacy (7). The interest of studying the efficacy of self-ligating brackets was not only limited to comparing self-ligating brackets to conventional brackets but extended to compare active self-ligating to passive self-ligating brackets (8).

On the other hand with the introduction of NiTi archwires into orthodontics, their use in the alignment and leveling stage was preferred because of their low modulus of elasticity, high springback, and wide force–delivery range. Attention to wire size and shape retreated in favor of the structural properties of the new wires (9). In other words, NiTi wires gained popularity in orthodontics because their use coincided with the notion of optimum orthodontic force, whereas orthodontics is in the midst of a paradigm shift, from the heavy forces of the past to appropriate gentle forces that are optimum for cellular response (10).

The objective of this study was to evaluate the amount of correction of complex orthodontic tooth malalignment achieved by various small cross-section archwire/bracket combinations using the orthodontic measurement and simulation system (OMSS).

Materials and methods

Study materials and design

The study comprised three types of orthodontic brackets 1) conventional ligating brackets (Victory Series; 3M Unitek, Monrovia, CA, USA; and Mini-Taurus, Rocky Mountain Orthodontics, Denver, CO, USA), 2) self-ligating brackets (SmartClip a passive self-ligating bracket; 3M Unitek and Time3 an active self-ligating bracket; American Orthodontics, Sheboygan, WI, USA) in addition to 3) a specially designed conventional low-friction bracket (Synergy; Rocky Mountain Orthodontics). All brackets had a nominal 0.022″ slot size. The brackets were combined with four arch wires: 0.012″ stainless steel (3M Unitek), 0.012″ Orthonol (Rocky Mountain Orthodontics), 0.012″ Thermalloy (Rocky Mountain Orthodontics), and 0.0155″ coaxial (Advanced Orthodontics; Näpflein GmbH, Düsseldorf, Germany). Archwires were combined to the conventional brackets with both stainless steel ligatures of size 0.010″ (Advanced Orthodontics; Näpflein GmbH) and elastomeric rings (3M Unitek). The correction of the complex malocclusion was tested 20 times for each archwire/bracket combination with the two types of ligation, thus a total of 640 tests was performed (Table 1).

Building a simulated maxillary dental arch of an orthodontic case

Resin replicas (Palavit G; Heraeus Kulzer GmbH, Hanau, Germany) were constructed from a Frasaco model (Franz Sachs & Co. GmbH, Tettnang, Germany) of a normally aligned upper arch. The right central incisor was removed from the resin model to allow for placement of the sensor of the testing OMSS (11,12). Brackets were bonded from second premolar to second premolar on the resin models with a cyanoacrylate adhesive. A jig was used to standardize the bonding process of the right central incisor bracket to a bracket holder that was attached to one sensor of the OMSS.

The self-ligating brackets in this study were used in the closed position. For the conventional

Table 1. **Study materials and design**

Bracket type	Bracket width (central incisor)	Bracket width (lateral incisor)	Type of ligation	Type of wire	Group observations	Total observations
Mini-Taurus	3.6 mm	3.1 mm	Stainless steel ligation	Stainless steel 0.012-in	20	640
			Elastic ligation	Coaxial 0.0155-in		
Victory Series	3.6 mm	2.9 mm	Stainless steel ligation	Orthonol 0.012-in		
			Elastic ligation	Thermalloy 0.012-in		
Synergy	3.4 mm	3.4 mm	Stainless steel ligation			
			Elastic ligation			
Smart-Clip	3.8 mm	3.3 mm	Passive self ligation			
Time3	2.5 mm	2.4 mm	Active self ligation			

brackets, the stainless steel ligatures used were tied using a needle holder, the ligature was first tightened around the bracket wings and then loosened one turn to allow free movement of the archwire. The elastomeric ligatures used were positioned using a needle holder, 3 min waiting period was allocated to allow a reproducible amount of stress relaxation to occur as recommended by Henao and Kusy (13).

Experimental setup

The OMSS (11,12) comprises two force–moment sensors capable of registering forces and moments in the three planes of space simultaneously. The two sensors are mounted on motor-driven positioning tables that can move freely in three planes of space. Commands regarding the conditions of the experiment are given to the OMSS through a personal computer. Two microcomputer-based sensor electronics deliver the digital output of the force–moment vectors to the personal computer where resultant force–deflection curves are recorded, thus facilitating a mean to study the loads from simulated orthodontic tooth movement. The whole mechanical assembly of the OMSS is built in a temperature-controlled chamber which is especially important when testing temperature-dependant alloys. The biomechanical principles of the OMSS are similar to the principles of the strain gauge apparatus used by Burstone to measure force and moments at the bracket in three planes (14,15).

Experimental procedures

To prepare the setup for measurements, the resin model was mounted on the OMSS table and the bracket holder with the bracket of the right central incisor bonded to it was fixed to the left sensor (see Fig. 1). Only the left measurement table was used for the current measurements. The sensor was then adjusted such that the bracket was in the right position in the prepared space in the resin model. The whole assembly now simulates the original aligned arch. Before starting the measurements cycle, the initial forces and moments exerted to the bracket and recorded by the sensors were adjusted as close to zero as possible. The malocclusion simulated in this study comprised a

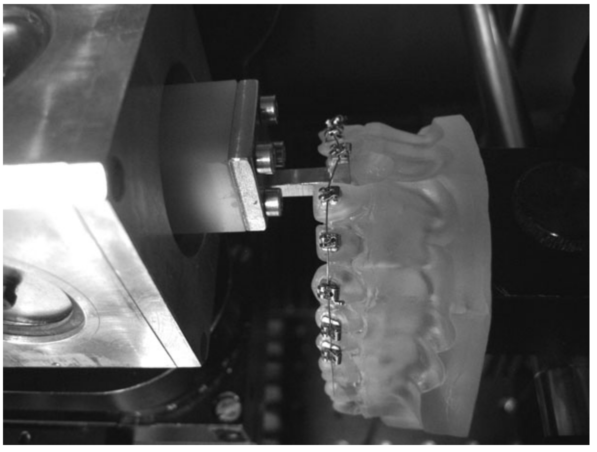

Fig. 1. Photograph of the orthodontic measurement and simulation system. The resin replica of a Frasaco model was integrated in the setup. Two millimeter gingival and 2 mm labial displacements of the test bracket were simulated at the position of the upper right central incisor.

gingival displacement of 2 mm and a labial displacement of 2 mm. Intrusion–extrusion movements were presented on the x-axis, while labio-lingual movements were represented on the z-axis. Thus, the OMSS was set to move the upper right central incisor from the initial position 2 mm gingivally (x-axis) and 2 mm labially (z-axis).

The correctional movement then took place automatically as a simulated tooth movement: The force system was measured in the displaced position, analyzed by the OMSS control software and processed to a vector of tooth movement. A mathematical model calculates a vector of tooth movement taking into account the center of resistance of the simulated tooth (12). The center of resistance of the simulated malaligned central incisor was positioned at 10 mm apically and 4.5 mm lingually to the point of force application. The vector of tooth movement was split up into small increments of below 0.01 mm (0.01°) and the motor-driven measurement table performed an increment of the calculated movement. The movement was stopped, and the force system was measured again. By repeating this cycle up to 200 times, the malposition of the tooth was corrected until no force or moment was active at the bracket. The quotient of the performed movement and the initial malposition was the efficacy of the correctional movement of the respective archwire/bracket combination.

During testing, both the Orthonol and Thermalloy wires, the temperature was kept at 37 (±1)°C.

Statistical analyses

The maximum absolute values of the correction of malalignment achieved in the two directions were calculated from the recordings of the OMSS software for each sample. Descriptive statistics including means, standard deviations, and maximum and minimum values were calculated for each archwire/bracket combination and were then statistically analyzed with two-way ANOVA followed by least significant tests. The data were analyzed using SAS/STAT (SAS Institute Inc., Cary, NC, USA) software for statistical analysis.

Results

Descriptive statistics of the correction in the x-axis (inciso-gingival) and in the z-axis (occluso-gingival) are presented in Tables 2 and 3, respectively. Figures 2 and 3 show bar graphs of the correction achieved by different bracket/wire combinations sorted by wire and bracket type, for steel ligation (Fig. 2) and elastic ligation (Fig. 3) compared to self-ligation.

The two-way ANOVA (Table 4) indicated a significant bracket-type effect ($p \le 0.000$) and wire-type effect ($p \le 0.000$) on the correction of the malalignment designed for this study. The results also indicated the presence of interaction ($p \le 0.000$) between the two variables.

The ANOVA results, Table 2, showed the effect of the bracket type on the inciso-gingival and labio-lingual malalignment correction. Mini-Taurus ligated with elastic ligatures to Coaxial, Orthonol, Thermalloy, and stainless steel wires showed a significantly smaller correction (0.5 ± 0.4, 0.3 ± 0.2, 0.3 ± 0.2 and 1.4 ± 0.1 mm, respectively, in the x-direction) and (0.3 ± 0.5, 0.5 ± 0.3, 0.3 ± 0.2, and 1.4 ± 0.2 mm, respectively, in the z-direction) and so did Victory Series brackets ligated with elastic ligatures to the same wires (1.1 ± 0.3, 0.3 ± 0.3, 0.5 ± 0.4, and 1.3 ± 0.1 mm, respectively, in the x-direction) and (0.2 ± 0.1, 0.5 ± 0.3, 0.4 ± 0.4, and 1.2 ± 0.2 mm, respectively, in the z-direction). Generally, the correction achieved with the coaxial, Orthonol, and Thermalloy wires was smaller than the correction achieved with the stainless steel wires.

The ANOVA results (Table 3) showed a significant effect of the type of archwire combined with the bracket on the level of the inciso-gingival and labio-lingual malalignment correction achieved. All the wires showed no significant difference in the degree of correction achieved with Time3 brackets with the exception of a larger degree of inciso-gingival correction when using stainless steel wires (1.6 ± 0.1) compared to the other wires. All the wires used showed no significant difference in the degree of correction achieved with SmartClip brackets with the

Table 2. **Descriptive statistics of the mean correction in *x* (inciso-gingival) and *z* (labio-lingual) directions: effect of bracket type**

		Bracket type							
Wire type	N	Mini-Taurus Steel ligation	Mini-Taurus Elastic ligation	Victory Series Steel ligation	Victory Series Elastic ligation	Synergy Steel ligation	Synergy Elastic ligation	Smart-Clip	Time3
Correction (x)axis									
Steel	20	1.6 ± 0.1^{c}	1.4 ± 0.1^{d}	1.8 ± 0.1^{a}	1.3 ± 0.1^{d}	1.6 ± 0.1^{bc}	1.7 ± 0.1^{b}	1.7 ± 0.2^{b}	1.6 ± 0.1^{bc}
		80 ± 5%	70 ± 5%	90 ± 5%	65 ± 5%	80 ± 5%	85 ± 5%	85 ± 10%	80 ± 5%
Coaxial	20	1.6 ± 0.2^{cb}	0.5 ± 0.4^{e}	1.7 ± 0.3^{ab}	1.1 ± 0.3^{d}	1.6 ± 0.3^{cb}	1.8 ± 0.1^{a}	1.7 ± 0.1^{ab}	1.5 ± 0.1^{c}
		80 ± 10%	25 ± 20%	85 ± 15%	55 ± 15%	80 ± 15%	90 ± 5%	85 ± 5%	75 ± 5%
Orthonol	20	1.8 ± 0.1^{ab}	0.3 ± 0.2^{d}	1.8 ± 0.1^{a}	0.3 ± 0.3^{d}	1.7 ± 0.3^{b}	1.7 ± 0.1^{ab}	1.7 ± 0.2^{b}	1.4 ± 0.3^{c}
		90 ± 5%	15 ± 10%	90 ± 5%	15 ± 15%	85 ± 15%	85 ± 5%	85 ± 10%	70 ± 15%
Thermalloy	20	1.5 ± 0.3^{c}	0.3 ± 0.2^{e}	1.5 ± 0.3^{c}	0.5 ± 0.4^{d}	1.7 ± 0.2^{ab}	1.6 ± 0.2^{cb}	1.8 ± 0.2^{a}	1.5 ± 0.3^{c}
		75 ± 15%	15 ± 10%	75 ± 15%	25 ± 20%	85 ± 10%	80 ± 10%	90 ± 5%	75 ± 15%
Correction (z)axis									
Steel	20	1.8 ± 0.1^{a}	1.4 ± 0.2^{d}	1.7 ± 0.1^{abc}	1.2 ± 0.2^{e}	1.6 ± 0.2^{bc}	1.6 ± 0.3^{c}	1.7 ± 0.2^{abc}	1.7 ± 0.2^{ab}
		90 ± 5%	70 ± 10%	85 ± 5%	60 ± 10%	80 ± 10%	80 ± 15%	85 ± 10%	85 ± 10%
Coaxial	20	1.6 ± 0.4^{a}	0.3 ± 0.5^{c}	1.5 ± 0.4^{a}	0.2 ± 0.1^{c}	1.0 ± 0.2^{b}	1.6 ± 0.4^{a}	1.7 ± 0.2^{a}	1.5 ± 0.4^{a}
		80 ± 20%	15 ± 25%	75 ± 20%	10 ± 5%	50 ± 10%	80 ± 20%	85 ± 10%	75 ± 20%
Orthonol	20	1.8 ± 0.1^{ab}	0.5 ± 0.3^{d}	1.8 ± 0.1^{b}	0.5 ± 0.3^{ad}	1.8 ± 0.3^{ab}	1.8 ± 0.2^{ab}	1.9 ± 0.1^{a}	1.5 ± 0.3^{c}
		90 ± 5%	25 ± 15%	90 ± 5%	25 ± 15%	90 ± 15%	90 ± 10%	95 ± 5%	75 ± 15%
Thermalloy	20	1.6 ± 0.2^{bcd}	0.3 ± 0.2^{e}	1.6 ± 0.3^{cd}	0.4 ± 0.4^{e}	1.8 ± 0.3^{ab}	1.8 ± 0.3^{abc}	1.9 ± 0.1^{a}	1.6 ± 0.4^{d}
		80 ± 10%	15 ± 10%	80 ± 15%	20 ± 20%	90 ± 15%	90 ± 15%	95 ± 5%	80 ± 20%

Mean values in each row with the same superscript letter are not significantly different at $p \leq 0.05$.

exception of a larger degree of labio-lingual correction when using Orthonol (1.9 ± 0.1) and Thermalloy (1.9 ± 0.1) wires compared with stainless steel (1.7 ± 0.2) and coaxial (1.7 ± 0.2) wires.

Discussion

The current study is an *in vitro* study and although *in vitro* experimental setups cannot replicate the oral environment, *in vitro* studies cannot be omitted in today's era of evidence-based dental practice. The oral environment could influence the results of an orthodontic mechanotherapy through 1) the biologic response of the periodontal attachment system, and 2) the effect on the surface texture of the archwires, brackets, and auxiliaries. Clinically the geometric asymmetry of the tooth and the periodontal ligament implies axes of resistance that do not intersect and therefore do not represent the center of resistance as a 3D point (16). Because the current experimental setup could be described as 'an idealized representation of the *in vivo* situation' the center of resistance was considered as a point in 3D (17) as described in the materials and methods section. On the other hand, till now, there is not enough evidence for the effects of aging of dental materials on orthodontic tooth movement (18). In the current study, certain measures have been taken to moderate the difference between the *in vitro* and *in vivo* experimental conditions, among them that 1) during testing, both for the Orthonol and Thermalloy wires, the temperature was kept at 37(±1)°C which was feasible by the mechanical assembly of the OMSS which is built

Table 3. **Descriptive statistics of the mean correction in *x* (inciso-gingival) and *z* (labio-lingual) directions: effect of wire type**

		Bracket type							
Wire type	N	Mini-Taurus Steel ligation	Mini-Taurus Elastic ligation	Victory Series Steel ligation	Victory Series Elastic ligation	Synergy Steel ligation	Synergy Elastic ligation	Smart-Clip	Time3
Correction (x) axis									
Steel	20	1.6 ± 0.1^{b}	1.4 ± 0.1^{a}	1.8 ± 0.1^{a}	1.3 ± 0.1^{a}	1.6 ± 0.1^{ab}	1.7 ± 0.1^{b}	1.7 ± 0.2^{a}	1.6 ± 0.1^{a}
		80 ± 5%	70 ± 5%	90 ± 5%	65 ± 5%	80 ± 5%	85 ± 5%	85 ± 10%	80 ± 5%
Coaxial	20	1.6 ± 0.2^{b}	0.5 ± 0.4^{b}	1.7 ± 0.3^{a}	1.1 ± 0.3^{b}	1.6 ± 0.3^{b}	1.8 ± 0.1^{a}	1.7 ± 0.1^{a}	1.5 ± 0.1^{ab}
		80 ± 10%	25 ± 20%	85 ± 15%	55 ± 15%	80 ± 15%	90 ± 5%	85 ± 5%	75 ± 5%
Orthonol	20	1.8 ± 0.1^{a}	0.3 ± 0.2^{c}	1.8 ± 0.1^{a}	0.3 ± 0.3^{c}	1.7 ± 0.3^{ab}	1.7 ± 0.1^{ab}	1.7 ± 0.2^{a}	1.4 ± 0.3^{b}
		90 ± 5%	15 ± 10%	90 ± 5%	15 ± 15%	85 ± 15%	85 ± 5%	85 ± 10%	70 ± 15%
Thermalloy	20	1.5 ± 0.3^{c}	0.3 ± 0.2^{c}	1.5 ± 0.3^{b}	0.5 ± 0.4^{c}	1.7 ± 0.2^{a}	1.6 ± 0.2^{c}	1.8 ± 0.2^{a}	1.5 ± 0.3^{ab}
		75 ± 15%	15 ± 10%	75 ± 15%	25 ± 20%	85 ± 10%	80 ± 10%	90 ± 5%	75 ± 15%
Correction (z) axis									
Steel	20	1.8 ± 0.1^{a}	1.4 ± 0.2^{a}	1.7 ± 0.1^{ab}	1.2 ± 0.2^{a}	1.6 ± 0.2^{b}	1.6 ± 0.3^{b}	1.7 ± 0.2^{b}	1.7 ± 0.2^{a}
		90 ± 5%	70 ± 10%	85 ± 5%	60 ± 10%	80 ± 10%	80 ± 15%	85 ± 10%	85 ± 10%
Coaxial	20	1.6 ± 0.4^{b}	0.3 ± 0.5^{c}	1.5 ± 0.4^{b}	0.2 ± 0.1^{c}	1.0 ± 0.2^{c}	1.6 ± 0.4^{ab}	1.7 ± 0.2^{b}	1.5 ± 0.4^{a}
		80 ± 20%	15 ± 25%	75 ± 20%	10 ± 5%	50 ± 10%	80 ± 20%	85 ± 10%	75 ± 20%
Orthonol	20	1.8 ± 0.1^{a}	0.5 ± 0.3^{b}	1.8 ± 0.1^{a}	0.5 ± 0.3^{b}	1.8 ± 0.3^{a}	1.8 ± 0.2^{a}	1.9 ± 0.1^{a}	1.5 ± 0.3^{a}
		90 ± 5%	25 ± 15%	90 ± 5%	25 ± 15%	90 ± 15%	90 ± 10%	95 ± 5%	75 ± 15%
Thermalloy	20	1.6 ± 0.2^{b}	0.3 ± 0.2^{c}	1.6 ± 0.3^{b}	0.4 ± 0.4^{cb}	1.8 ± 0.3^{a}	1.8 ± 0.3^{ab}	1.9 ± 0.1^{a}	1.6 ± 0.4^{a}
		80 ± 10%	15 ± 10%	80 ± 15%	20 ± 20%	90 ± 15%	90 ± 15%	95 ± 5%	80 ± 20%

Mean values in each column with the same superscript letter are not significantly different at $p \leq 0.05$.

in a temperature-controlled chamber, 2) the simulated malocclusion was kept to the minimal malocclusion (2 mm inciso-gingival and 2 mm labio-lingual) which means that this malalignment clinically could be solved in one or two orthodontic visits 4–6 weeks apart.

Different ligation methods were used, and it was interpreted from the results that ligation type had significantly influenced the degree of correction achieved. The degree of correction was significantly smaller when elastic ligature was used with Mini-Taurus and Victory Series brackets: The inciso-gingival correction with the Victory Series system ranged from 15 to 65% with the different archwires and the labio-lingual correction ranged from 10 to 60% while with the Mini-Taurus system the inciso-gingival and the labio-lingual corrections ranged from 15 to 70% with the different archwires. This interesting result could be attributed to the frictional force generated between the bracket and the archwire. Friction is influenced by the physical characteristics of the archwire and bracket materials, bracket design, and the method of attachment between archwire and bracket (19–26). Elastic ligatures when used with conventional brackets increased the levels of frictional resistance. (27)

Self-ligating brackets combined with different archwires have been associated, in previous studies, with friction reduction (13,25–27). In alignment with these results, the least inciso-gingival correction achieved in this study when self-ligating brackets were used in combination with different archwires was 70% and the least labio-lingual correction was 75%. In the current study, SmartClip and Time3 self-ligating brackets and Victory Series and Mini-Taurus conventional brackets ligated with stainless steel ligature showed a large degree of consistency in the inciso-gingival and labio-lingual correction achieved with all the wires. Generally, the degree of correction was comparable between these

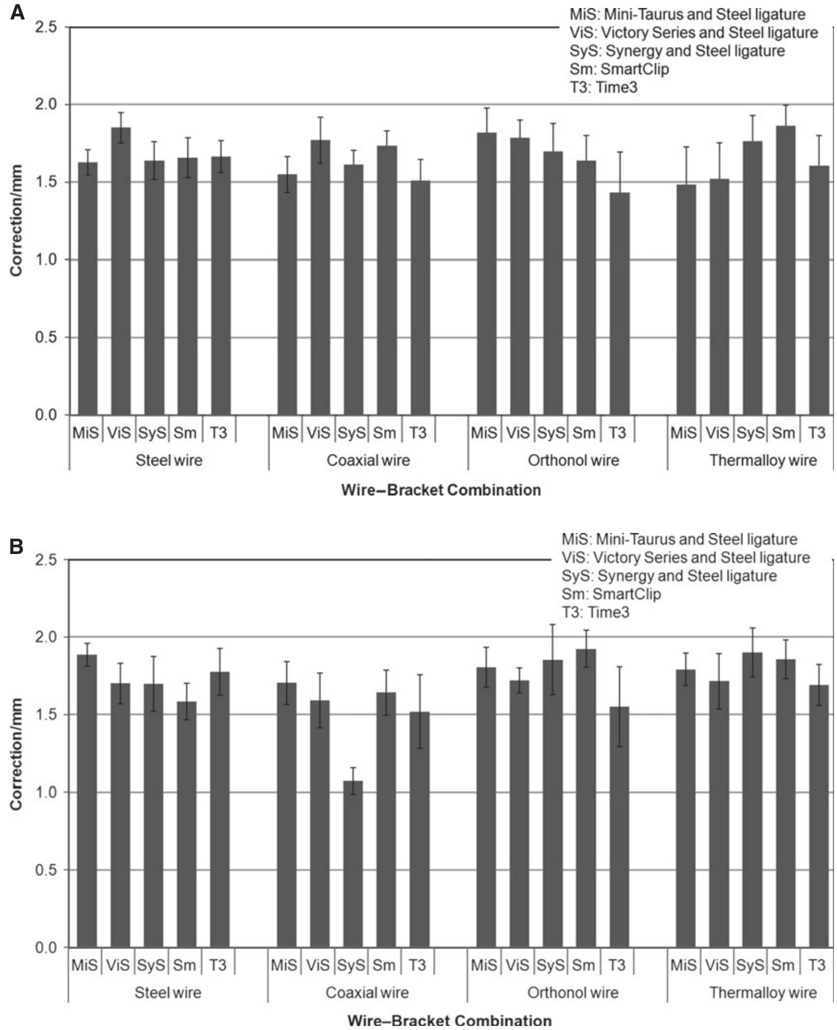

Fig. 2. (A) Maximum correction in the *x*-direction (extrusive movement), and (B) maximum correction in the *z*-direction (lingual movement) for conventional brackets ligated with a stainless steel ligature and for self-ligating brackets.

different combinations. Using the OMSS system (28) to test the leveling effectiveness of nine self-ligating bracket systems and a conventional bracket system ligated with stainless steel ligatures, both self-ligating brackets and conventional brackets behaved similarly, therefore, self-ligating brackets were not found superior to conventional brackets in terms of their biomechanical characteristics.

The results of the current study showed bracket type to have a significant effect on the correction achieved, which was largely attributed to the type of ligation of the brackets, whether it is active self-ligation, passive self-ligation, elastic or stainless steel conventional ligation. However, other factors in the design of the bracket should be considered as well. This could best be discussed based on the correction achieved with Synergy brackets. The effect of ligation when used with Synergy brackets was different; Synergy brackets ligated with elastic ligature behaved differently than conventional brackets ligated with the same type of ligature as it produced 80–90% correction in both directions with the different wires used. Synergy brackets ligated with elastic ligation produced a larger or comparable degree of correction to steel ligation with all wire types. The Synergy bracket had six tie wings of which the central wings are raised so the slot walls prevent contact between the wire and the ligature and this was the protocol followed in this study. With this protocol of ligation, a free play of the archwire was ensured with both stainless steel ligature and the elastomeric ligation. Also, with this protocol the inter-bracket distance increases and as the distance increases between the points of attachment of a beam springiness increases rapidly (29). This

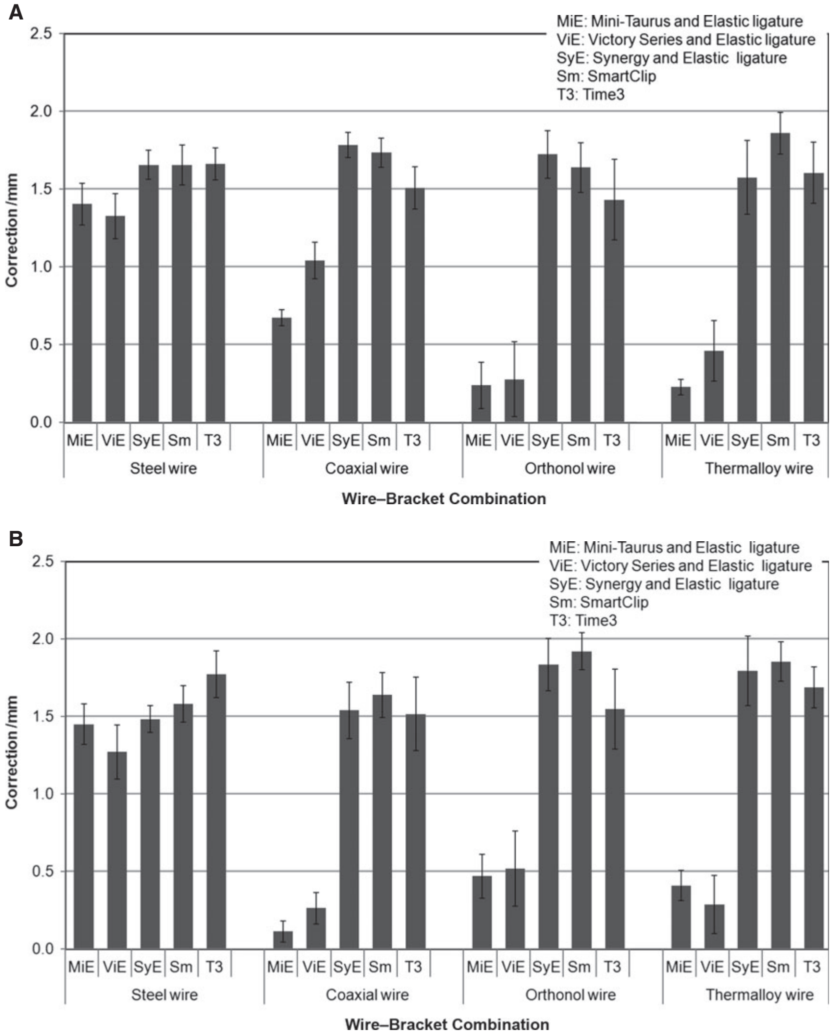

Fig. 3. (A) Maximum correction in the *x*-direction (extrusive movement), and (B) maximum correction in the *z*-direction (lingual movement) for conventional brackets ligated with elastomeric rings and for self-ligating brackets.

Table 4. **Results of two-way ANOVA of the correction for the bracket/wire combinations**

	Two-way ANOVA			
	Sum of squares	df	*F*	*p* Value
A (Force in *x* direction)				
Brackets	106.29	7	305.67	≤0.000
Wires	8.13	3	54.55	≤0.000
Brackets × Wires	24.58	21	23.56	≤0.000
B (Force in *z* direction)				
Brackets	133.08	7	202.09	≤0.000
Wires	13.87	3	49.16	≤0.000
Brackets × Wires	26.19	21	13.26	≤0.000

consistent result was not seen in the *x*-axis, which represents the intrusion–extrusion direction; this could have happened because in this direction the slot walls have more influential effect on the force level than the type of ligature used.

The findings of the comparisons of the clinical effectiveness of conventional and self-ligating bracket systems for initial alignment were not always consistent. The effectiveness of correction of SmartClip and conventional brackets was not different. The type of ligation used, whether elastic or stainless steel, showed no effect on the effectiveness of correction (30,31). Comparing the efficacy of Damon 3MX self-ligating and conventional brackets during the first 5 months of extraction treatment showed that self-ligating brackets were not more efficient than conventional ligating brackets in anterior alignment and that ligation is only one of many factors that can influence the efficacy of treatment (32). On the other hand, conventional brackets showed 98% correction compared with 67% for Damon 3 self-ligating brackets after 4 months of alignment and leveling. Conventional brackets showed faster alignment of teeth than self-ligating brackets specially in the first month (33). Systematic review of the clinical studies on effectiveness, efficacy, and stability of treatment of conventional and self-ligating brackets found no evidence of the claimed advantages of self-ligating brackets (34,35).

Generally, in the current study, a noticeable increase in the correction was observed with stainless steel wires even when elastic ligature was used compared with the correction achieved with coaxial, Orthonol, and Thermalloy wires which infers a significant effect of the archwire type used. This high correction with stainless steel wire might be attributed to the increased forces exerted by these wires. A previous *in vitro* study (36) measured the forces generated during complex orthodontic tooth movements with various archwire/bracket combinations. The study reported the lowest forces for the brackets when combined with either the coaxial or the Thermalloy archwires: the forces ranged from 3.4 ± 0.2 to 0.7 ± 0.1 N in the inciso-gingival direction, and from 4.5 ± 0.3 to 0.5 ± 0.1 N in the labio-lingual direction. The highest forces were measured in combination with stainless steel archwires and ranged from 6.3 ± 0.3 to 3.0 ± 0.1 N in the inciso-gingival direction, and from 6.3 ± 0.3 to 1.7 ± 0.1 N in the labio-lingual direction.

Therefore, the force exerted on teeth should not be overlooked when evaluating efficiency of alignment. As concluded previously, it is important to evaluate any orthodontic appliance system for its ability to align teeth rapidly and predictably, but with minimal deleterious effects to the oral tissues (2).

Conclusions

The resultant tooth alignment was the product of interaction between the bracket type, wire type, and bracket design. Small cross-sectional archwires might produce up to 95% malalignment correction if combined properly with the bracket system. Elastomeric rings when used with conventional brackets limit the efficacy of tooth alignment. Forces exerted on teeth should not be overlooked when evaluating efficacy of tooth alignment.

Clinical relevance

Orthodontics witnessed a great leap in the efficacy of orthodontic mechanics and a big move from heavy forces to optimal forces. Because forces exerted on teeth should not be overlooked when choosing an archwire/bracket combination, the correction of complex orthodontic tooth malalignment achieved by small cross-sectional archwires combined with different conventional and self-ligating brackets was evaluated in this study. Wide variations of inciso-gingival correction ranging from 15 to 95%, and labio-lingual correction ranging from 10 to 95% were achieved. Certain small cross-sectional archwires are recommended for clinical use when combined with the proper bracket systems.

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References

1. Turnbull NR, Birnie DJ. Treatment efficiency of conventional vs self-ligating brackets: effects of archwire size and material. *Am J Orthod Dentofacial Orthop* 2007;131:395–9.
2. Scott P, DiBiase AT, Sherriff M, Cobourne M. Alignment efficiency of Damon3 self-ligating and conventional orthodontic bracket systems: a randomized clinical trial. *Am J Orthod Dentofacial Orthop* 2008;134:470.e1–470.e8.
3. Fleming PS, DiBiase AT, Lee RT. Randomized clinical trial of orthodontic treatment efficiency with self-ligating and conventional fixed orthodontic appliances. *Am J Orthod Dentofacial Orthop* 2010;137:738–42.
4. Eberting JJ, Straja SR, Tuncay OC. Treatment time, outcome, and patient satisfaction comparisons of Damon and conventional brackets. *Clin Orthod Res* 2001;4:228–34.
5. Fink DF, Smith RJ. The duration of orthodontic treatment. *Am J Orthod Dentofacial Orthop* 1992;102:45–51.
6. Shia GJ. Treatment overruns. *J Clin Orthod* 1986;20:602–4.
7. Cacciafesta V, Sfondrini MF. Correction of horizontal and vertical discrepancies with a new interactive self-ligating bracket system: the

Quick system. *World J Orthod* 2010;11:404–12.
8. Pandis N, Polychronopoulou A, Eliades T. Active or passive self-ligating brackets? A randomized controlled trial of comparative efficiency in resolving maxillary anterior crowding in adolescents. *Am J Orthod Dentofacial Orthop* 2010;137:12.e1–12.e6.
9. Kusy RP. A review of contemporary archwires: their properties and characteristics. *Angle Orthod* 1997;67:197–208.
10. Bach RM. Self-ligation is not a scientific concept. *Am J Orthod Dentofacial Orthop* 2009;136:757.
11. Drescher D, Bourauel C, Thier M. Application of the orthodontic measurement and simulation system (OMSS) in orthodontics. *Eur J Orthod* 1991;13:169–78.
12. Bourauel C, Drescher D, Thier M. An experimental apparatus for the simulation of three-dimensional movements in orthodontics. *J Biomed Eng* 1992;14:371–8.
13. Henao SP, Kusy RP. Evaluation of the frictional resistance of conventional and self-ligating bracket designs using standardized archwires and dental typodonts. *Angle Orthod* 2004;74:202–11.
14. Burstone CJ, Koenig HA. Force systems from an ideal arch. *Am J Orthod* 1974;65:270–89.
15. Burstone CJ. Application of bioengineering to clinical orthodontics. In: Graber TM, Swain BF, editors. *Orthodontics: Current Principles and Techniques*. St Louis: Mosby; 1985. pp. 193–228.
16. Viecilli RF, Budiman A, Burstone CJ. Axes of resistance for tooth movement: does the center of resistance exist in 3-dimensional space? *Am J Orthod Dentofacial Orthop* 2013;143:163–72.
17. Burstone CJ, Pryputniewicz RJ. Holographic determination of centers of rotation produced by orthodontic forces. *Am J Orthod* 1980;77:396–409.
18. Eliades T, Bourauel C. Intraoral aging of orthodontic materials: the picture we miss and its clinical relevance. *Am J Orthod Dentofacial Orthop* 2005;127:403–12.
19. Tidy DC. Frictional forces in fixed appliances. *Am J Orthod Dentofacial Orthop* 1989;96:249–54.
20. Ireland AJ, Sherriff M, McDonald F. Effect of bracket and wire composition on frictional forces. *Eur J Orthod* 1991;13:322–8.
21. Taylor NG, Ison K. Frictional resistance between orthodontic brackets and archwires in the buccal segments. *Angle Orthod* 1996;66:215–22.
22. Michelberger DJ, Eadie RL, Faulkner MG, Glover KE, Prasad NG, Major PW. The friction and wear patterns of orthodontic brackets and archwires in the dry state. *Am J Orthod Dentofacial Orthop* 2000;118:662–74.
23. Pizzoni L, Ravnholt G, Melsen B. Frictional forces related to self-ligating brackets. *Eur J Orthod* 1998;20:283–91.
24. Schumacher HA, Bourauel C, Drescher D. The influence of bracket design on frictional losses in the bracket/arch wire system. *J Orofac Orthop* 1999;60:335–47.
25. Read-Ward GE, Jones SP, Davies EH. A comparison of self-ligating and conventional orthodontic bracket systems. *Br J Orthod* 1997;24:309–17.
26. Thorstenson GA, Kusy RP. Resistance to sliding of self-ligating brackets versus conventional stainless steel twin brackets with second-order angulation in the dry and wet (saliva) states. *Am J Orthod Dentofacial Orthop* 2001;120:361–70.
27. Khambay B, Millett D, McHugh S. Evaluation of methods of archwire ligation on frictional resistance. *Eur J Orthod* 2004;26:327–32.
28. Fansa M, Keilig L, Reimann S, Jäger A, Bourauel C. The leveling effectiveness of self-ligating and conventional brackets for complex tooth malalignments. *J Orofac Orthop* 2009;70:285–96.
29. Proffit WR, Fields HW, Sarver DM. *Contemporary Orthodontics*, 4th edn. St Louis: Mosby; 2007. pp. 359–361, 555.
30. Miles PG. SmartClip versus conventional twin brackets for initial alignment: is there a difference? *Aust Orthod J* 2005;21:123–7.
31. Fleming PS, DiBiase AT, Sarri G, Lee RT. Efficiency of mandibular arch alignment with 2 preadjusted edgewise appliances. *Am J Orthod Dentofacial Orthop* 2009;135:597–602.
32. Ong E, McCallum H, Griffin MP, Ho C. Efficiency of self-ligating vs conventionally ligated brackets during initial alignment. *Am J Orthod Dentofacial Orthop* 2010;138:138.e1–138.e7.
33. Wahab RM, Idris H, Yacob H, Ariffin SH. Comparison of self- and conventional-ligating brackets in the alignment stage. *Eur J Orthod* 2012;34:176–81.
34. Chen SS, Greenlee GM, Kim JE, Smith CL, Huangd GJ. Systematic review of self-ligating brackets. *Am J Orthod Dentofacial Orthop* 2010;137:726.e1–726.e18, discussion 726–727.
35. Fleming PS, Johal A. Self-ligating brackets in orthodontics. A systematic review. *Angle Orthod* 2010;80:575–84.
36. Montasser MA, El-Bialy T, Keilig L, Reimann S, Jäger A, Bourauel C. Force levels in complex tooth alignment with conventional and self-ligating brackets. *Am J Orthod Dentofacial Orthop* 2013;143:507–14.