The combined effect of bracket design, archwire cross-section and alloy on orthodontic forces, moments and the resultant tooth alignment

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Chrystalla Kyprianou

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1. Gutachter: Prof. Dr. rer. nat. Christoph Bourauel

2. Gutachter: Prof.Dr.Stefan Lossdörfer

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Direktor: Prof. Dr. med. dent. Helmut Stark

- Stiftungsprofessur für Oralmedizinische Technologie -

Prof. Dr. rer. nat. Christoph Bourauel

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List of Abbreviations

3D	three-dimensional
ANOVA	Analysis of Variance
Fx	Force on the x - axis / intrusion-extrusion
Fy	Force on the y – axis / mesiodistal
Fz	Force on the z – axis / orovestibular
i.e.	„id est“ (Latin) ~ „that is“ (English)
Mx	Moment on the x - axis / rotation
My	Moment on the y - axis / torque
Mz	Moment on the z - axis / tipping
NiTi	Nickel Titanium
OMSS	Orthodontic Measurement and Simulation System
p	probability value
Rx	Rotational position on the x - axis
Ry	Rotational position on the y - axis
SS	Stainless Steel
Tx	Linear position on the x - axis
Ty	Linear position on the y - axis
Tz	Linear position on the z - axis
β-Ti	Beta Titanium
“	inch (=25.4 mm; in this thesis the unit inch is used as brackets and wires are dimensioned in inches)

1. English summary

1.1 Introduction

The complete customization of lingual bracket systems aimed to overcome the disadvantages of traditional lingual orthodontic methods, such as patient discomfort and poor clinical efficiency (George and Hirani, 2013). While patients prioritize comfort and aesthetics, orthodontic professionals consider clinical performance as a determining factor in the choice of any orthodontic appliance (Marañón-Vásquez et al., 2021). Systematic reviews of clinical trials, investigating the therapeutic or adverse effects of lingual orthodontics, confirmed that more studies are needed in order to extract safe conclusions (Mistakidis et al., 2016; Binhuwaishel and Al-Jewair, 2018). In vitro studies were conducted in order to evaluate fully customized lingual appliances, in relation to forces and moments, with conflicting results (Fuck et al., 2005; Sifakakis et al., 2013).

Nickel titanium, beta titanium and stainless steel are currently the most frequently used alloys in the production industry of orthodontic archwires. Although the mechanical biocompatibilities of these alloys were standarized to levels proper for biomedical applications, cross-sectional or shape variations can affect the generated force/moment values and the consequent biologic response during orthodontic movement (Sifakakis et al., 2014; Montasser et al., 2016). Each orthodontic archwire sequence should ensure patient comfort, suitable treatment duration and optimal treatment outcome. Systematic reviews of clinical trials showed that there is inadequate research evidence to draw a distinction between a variety of initial archwires or archwire sequences (Papageorgiou et al., 2014; Wang et al., 2018).

The load transmitted to the dental arch during orthodontic alignment should be low enough in order to prevent damage to the teeth or/and the periodontal tissues. Apart from the factors related to any bracket/wire combination, forces and moments are subject to the amount of misalignment. Dissimilar tooth types are able to withstand different loads depending on their morphological characteristics (Proffit et al., 2007; Papageorgiou et al., 2017).

The main purpose of this study was to compare forces and moments generated from conventional labial and fully customized lingual bracket systems combined with wires of different alloys and various dimensions for the alignment of certain teeth. Different testing protocols were established in order to fill the gaps in existing literature. Firstly, this study aimed to simulate the leveling process of a specific malocclusion model with the use of a NiTi archwire sequence in order to analyze the initial forces and moments generated at every alignment stage, as well as the final tooth positions. Secondly, this investigation aimed to compare the force values produced from the activation of 0.018” x 0.025” stainless steel and beta titanium wires under predefined conditions.

1.2 Materials and Methods

The experiment was carried out with two fully customized lingual bracket appliances, i.e. (i) Incognito™ (3M Unitek, Monrovia, CA, USA), (ii) WiN (DW Lingual Systems, Bad Essen, Germany) and two conventional labial systems, i.e. (i) Discovery® MIM, (ii) Discovery® smart (Dentaurum, Ispringen, Germany) combined with 0.012”, 0.014”, 0.016”, 0.016” x 0.022” NiTi, 0.018” x 0.025” β-Ti and 0.018” x 0.025” SS archwires.

Initially, an impression of the mandibular arch of a patient (Figure 1, Publication 1) was dispatched to a WiN laboratory to manufacture a full set of lingual brackets, a transfer tray and a setup model. As soon as the setup model was received and scanned, the digital version was forwarded to Incognito™ to facilitate the fabrication of an appliance with comparable therapeutic design. Customized mushroom-shaped archwires with straight lateral segments were acquired from the respective laboratories in addition to the lingual brackets, and preformed mandibular archwires, i.e. Tensic®, Rematitan® and Remanium® ideal arches (Dentaurum, Ispringen, Germany) were ordered together with the conventional labial appliances.

1.2.1 Simulation procedure

The malocclusion model was replicated with resin (Technovit® 4004, Kulzer GmbH, Hanau, Germany) in silicone molds. The labial brackets were bonded on the resin casts according to a direct bonding protocol with the use of a 0.018” x 0.025” SS splint, whereas for the lingual appliances, the customized transfer trays were utilized for indirect bonding.

The Transbond™ XT Light Cure adhesive primer and paste (3M Unitek, Monrovia, CA, USA) were chosen for the labial appliances and the Maximum Cure® sealants A and B (Reliance Orthodontics, Itasca, IL, USA) were chosen for the lingual systems as bonding agents.

The apparatus allowed movement of only one tooth at a time, therefore three teeth, i.e. a canine (#33), a lateral incisor (#42) and a second premolar (#45) were selected for the specific investigation. The objective was to experiment on teeth with different morphological characteristics, linear and rotational positions. Prior to the bonding of the appliances, all the selected teeth were separated from the replicas. The respective brackets were attached to a sensor fixed in the simulation chamber at a position parallel to the three planes of space. Afterwards, a resin cast bonded with one of the appliances was adjusted in the chamber with the use of the transfer trays or the wire splints. Subsequently, a 0.012" NiTi wire was inserted, ligated with short, preformed SS ligatures (Remanium®, Dentaurum, Ispringen, Germany) and the initial force was registered. The simulated movement was run until no forces or moments were detected from the sensor. At the balance position, the initial wire was replaced with the next et cetera until all NiTi wires were examined. For each appliance, the simulation process was repeated five times at every tooth position.

1.2.2 Activation procedure

Due to the rigid nature of the 0.018" x 0.025" archwires, a different testing protocol was followed. The setup model was replicated along with the malocclusion model. After the completion of the simulation, the bracket appliances were carefully transferred on the setup-resin duplicates by use of the direct bonding protocol. A cast was adjusted in the activation chamber in a position where all forces were eliminated and the selected archwire piece was ligated on the appliance. The sensor was programmed to perform successive steps of 0.02 mm for a distance of 0.2 mm on the x-axis and then backwards to the initial position of the tooth. The wire was, then, readjusted, ligated with new ligatures and the activation was repeated on the z-axis. The generated force values were recorded on 0.1 and 0.2 mm.

A manual ratchet thimble micrometer (Mitutoyo, Illinois, USA) and an electronic caliper (Digimatic 500-120, Mitutoyo, Neuss, Germany) were used to record interbracket distances, slot lengths and wire dimensions.

1.2.3 Apparatus

The OMSS (Bourauel et al., 1992) consists of a temperature-controlled chamber, which contains two 3D force/moment sensors connected with 3D positioning tables. For this experiment, the temperature was set at 37 °C to approximate intraoral temperature. The positioning tables are attached to microstepping motors and thus, this apparatus constitutes an electronic typodont, in which the positioning tables substitute the wax and allow tooth movement under the influence of force/moment. In detail, the sensors constantly detect the forces and moments generated from the specific bracket/wire combination and the software calculates the force/moment vectors. The resulted vector corresponds to the amount of movement, which is executed by the stepping motors by steps in the range of 10 micrometers and 0.1 degree.

1.2.4 Specifics

Incognito™ manufactures 0.0182” x 0.025”- archwires, while the rest of the brands offer wires of 0.018” x 0.025”.

For every rerun, a new wire piece and new ligatures were used. WiN customized only one set of wires, so for every repetition the same piece was readjusted and religated.

For both protocols, the wires were ligated only on the tested tooth and its adjacent teeth due to the rigid nature of the resin cast, which allows sole movement of the tooth under examination.

1.2.5 Statistical analysis

The statistical analysis was carried out in SPSS Statistics software version 9 (IBM, Armonk, New York, USA). Normal distribution of the registered data was proven using a Kolmogorov-Smirnov test ($p \leq 0.01$). Variances between the produced forces, moments and final positions of the selected teeth were analyzed with ANOVA. Student Newman Keuls tests ($p \leq 0.05$) were selected as Post-hoc tests, Student’s t-tests for equality of means ($p \leq 0.05$) were selected for group comparisons, and the standard deviations were compared with the use of Levene’s test of equality of variances ($p \leq 0.05$).

1.3 Results

1.3.1 Simulation procedure

The mesiodistal force and ultimate placement of the sensor on the same axis are of minimal importance for this investigation; therefore, Fy and Ty are not analyzed.

1.3.1.1 Forces

As shown in Tables II-V, Publication 1, lower orovestibular forces were recorded from labial systems when combined with all wires of the NiTi sequence [Fz; (p=0.000), (p=0.000), (p=0.012), (p=0.028)] for the lateral incisor compared with the lingual ones. For the canine, the higher orovestibular force (1.5 N) [Fz; p=0.000] registered using the 0.012" wire was produced by Incognito™, while both lingual appliances generated higher intrusion/extrusion forces when combined with the rectangular wire in comparison with the labial appliances [Table V; Fx; p=0.001]. Incognito™ generated, also, reverse intrusion/extrusion forces for both #33 and #42 compared with the rest of the appliances. For the premolar, Discovery® classic produced the highest registered orovestibular force (1.2 N) [Fz; p=0.000]. The use of 0.14", 0.016", 0.016" x 0.022" wires resulted in forces of different directions during the same stages of the tooth alignment.

1.3.1.2 Moments

Tables VI-IX, Publication 1 show the moment values produced by all bracket/archwire combinations. At the lateral incisor, higher rotational moments were produced from WiN (2.8 Nmm) and Incognito™ (3.6 Nmm) [Table VI; Mx; p=0.000] and higher torque (25.5 Nmm) was generated by WiN [Table VI; My; p=0.000] when these appliances were combined with the 0.012" wire. For the rest of the wires, WiN generated higher torque levels compared with the labial systems at the same area [Table VII-IX; My; (p=0.002), (p=0.018), (p=0.012)]. Also, Incognito™ produced moment values, which differed statistically and significantly from those recorded from the rest of the systems during the simulated movement of the lateral incisor and canine. Ligation of the initial wire at the canine area led to lower rotational moments (0.4 Nmm) produced from WiN [Table VI; Mx; p=0.000], higher tipping moments (-10 Nmm) and reverse torque values produced from Incognito™ [Table VI; Mz; p=0.006] compared with the rest of the appliances. Furthermore, the combination of 0.014" and 0.016" wires with WiN gave rise to lower rotational values (1.0 Nmm and 1.4 Nmm respectively) by WiN [Table VII-VIII; Mx ; (p=0.000), (p=0.002)] compared with the rest of the systems at the canine area. All the moments produced during the alignment of the premolar with the lingual appliances were statistically significantly lower than those generated from the labial appliances. In specific cases the variances were not marked as being statistically significant [Table VIII-IX; Mx; (p= 0.107), (p=0.230)]. The apparatus registered moments of different directions between the four appliances with the use of 0.14”, 0.016” and 0.016” x 0.022” wires at the same axis and same tooth area.

1.3.1.3 Final positions

In this study, linear or rotational final position is considered the position of each tooth at the balance point of the 0.016” x 0.022” NiTi archwire, which is presented in Tables X-XI, Publication 1. The canine was less rotated with the use of the WiN system (2.0°), most rotated with the use of Discovery® smart (11.7°), while Incognito™ rotated the specific tooth in a reverse direction (-7.8°) compared with the rest of the appliances [Table XI; Rx; p=0.000]. With Incognito™, the same variation was observed for the final vertical position (-0.7mm) of the canine [Table X; Tx; p=0.000] and the rotation of lateral incisor around the y-axis (-5.3°) [Table XI; Ry; p=0.000]. The minimum rotation of the premolar was observed with the use of the WiN appliance (1.8°), which presented slight difference from the Incognito™ system (2.3°). The Discovery® MIM and smart systems rotated the premolar more (7.3° and 10.9° respectively) [Table XI; Rx; p=0.000]. The same tooth was also directed more vestibulary with the use of the fully customized lingual bracket systems [Table X; Tz; p=0.000].

1.3.2 Activation procedure

Tables 4-7, Publication 2 display the analysis of the forces registered during activation. For the β-Ti wires, higher force levels were observed only in the cases shown in Figure 3, Publication 2. In all other cases, higher force levels were recorded with the use of SS archwires.

The measured slot widths, interbracket distances and wire dimensions are shown in Tables 2 and 3, Publication 2.

1.3.2.1 Stainless steel archwires

Combination of 0.018” x 0.025” SS archwires with WiN and Incognito™ generated higher forces during intrusion/extrusion of the premolar [(Table 4; #45; Fx; 0.1 mm; p=0.000 and 0.2 mm; p =0.000), (Table 5; #45; Fx; 0.1 mm; p=0.000 and 0.2 mm; p=0.022)] and during extrusion of the lateral incisor and the canine in comparison to labial appliances [Table 4; (#33; Fx; 0.1 mm; p=0.000 and 0.2 mm; p=0.000), (#42; Fx; 0.1 mm; p=0.000 and 0.2 mm; p=0.000)]. Oral movement of the lateral incisor and the premolar resulted in similar force levels for all tested systems [Table 5; #42; Fz; 0.1 mm; p=0.699 and 0.2 mm; p=0.451); (#45; 0.2 mm; Fz; p=0.388)].

1.3.2.2 Beta titanium archwires

As in the experimentation with SS wires, intrusion/extrusion forces at the premolar [(Table 6; #45; Fx; 0.1 mm; p=0.000 and 0.2 mm; p =0.000), (Table 7; #45; Fx; 0.1 mm; p=0.000 and 0.2 mm; p=0.000)] and lateral incisor area [(Table 6; #42; Fx; 0.1 mm; p=0.000), (Table 7; #42; Fx; 0.1 mm; p=0.000 and 0.2 mm; p=0.000)], as well as extrusion forces at the canine area [Table 7; #33; Fx; 0.1 mm; p=0.000 and 0.2 mm; p=0.000] were higher with the use of lingual appliances. Similar forces were observed throughout orovestibular activation of β-Ti archwires at the lateral incisor [Table 6; #42; Fz; 0.1 mm; p=0.264].

1.4 Discussion

ANOVA underlined the statistically significant differences between forces and moments produced by the selected bracket/wire combinations. The clinical importance of each statistically significant difference should be evaluated separately and with caution. Slight variations, due to inconsistent wire ligation pressure and unalike wire adjustment, could not influence the course of orthodontic treatment.

The values recorded during repetitions varied in many cases due to technical reasons. Deviations of wire dimensions can occur during manufacturing and could affect the generated force and moment levels (Pompei-Reynolds and Kanavakis, 2014). In addition, a measurement error could occur from the successive sensor adjustments and archwire changes, which alter the contact status between each bracket and wire.

As in the differences observed between the five repetitions, inconsistent wire ligation and unalike wire adjustment could affect the generated force/moment levels between positive and negative activations. Furthermore, the resistance created from the ligature is less than the one generated from the slot walls, thus force levels can be lower.

The slot width and the direction of the slot walls of each bracket determine the free wire length and the consequent wire stiffness, as well as the orientation of the inserted rectangular archwire. The long slot walls were oriented vertically for lingual bracket systems with a vertical slot opening at the anterior region (Supplementary Figures, Publication 1). The ribbon-wise configuration of the customized rectangular archwires led to higher intrusion/extrusion forces in comparison with the orovestibular forces generated from the same appliances and the intrusion/extrusion forces generated from the labial appliances. Due to reduced free wire space (Creekmore, 1976; Moran, 1987) between the lateral incisor and its adjacent teeth, lingual bracket appliances generated higher orovestibular forces than those generated from the labial appliances during experimentation with the NiTi wire sequence. The higher intrusion/extrusion forces recorded at tooth #33 during the final stage of the alignment with the lingual bracket systems result from the vertical orientation of the 0.016” x 0.022” NiTi archwire.

As in any wire sequence, the values registered from each archwire were dependent on the amount of force/moment applied by the previous wire of the sequence, which defined the amount of alignment needed until equilibrium was reached. The amount of residuary misalignment of tooth #42 and #45 was small, thus the rectangular wires generated lower forces. In cases where the levelling achieved from the chosen wire sequence is not enough, additional wires of small dimensions could be used prior to the finishing wire. The vertical configuration of the archwires could also result in lower orovestibular forces in comparison with the labial appliances, something that was not observed during activation of the 0.018” x 0.025” archwires due to the smaller lingual interbracket distances. Archwires of 0.018” x 0.025” are combined with lingual appliances when high torque expression is needed (β-Ti) or for segmental stabilization (SS). In addition, SS wires of these dimensions are indicated to increase anchorage during treatment with Herbst device (Vu et al., 2012; Mujagik et al., 2020). In clinical reality, the higher forces registered by use of lingual appliances could be translated in increased anchorage (Bock et al., 2016).

During simulation, experimentation with the Incognito™ system resulted in higher registered force levels and diverse moments at teeth #33 and #42, as well as different final tooth positions in comparison with the rest of the appliances. A possible explanation could be a differentiation of the transfer tray or the customized archwires received from Incognito™, which affected the simulation and resulted in different final tooth positions.

Moment values tended to differ between labial and lingual appliances. Lower moments were registered during experimentation with the WiN appliance at tooth #33, which resulted in less rotation of the canine. By use of archwires with straight lateral segments, both lingual bracket systems rotated tooth #45 less than labial appliances. Customization of the lateral segments could result in a different final position. Support with elastic chain could also be used in clinical practice when increased rotation is needed (Wiechmann and Nesbit, 2007).

The biomechanical characteristics of β-Ti and SS differ enough in order to cover several indications. Beta titanium presents lower strength, stiffness and elastic modulus in comparison with the stainless steel archwires, thus are considered a safer option when low force levels are required (Kusy, 1997; Proffit et al, 2007). On the other hand, β-Ti wires exhibit higher friction levels (Sridharan et al., 2017), as well as higher surface roughness than the SS wires. The coexistance of high roughness and increased friction levels is still questioned (Fidalgo et al., 2011; Doshi and Bhad-Patil, 2011). In this study, stainless steel wires were slightly smaller than the β-Ti ones and as a result, the slot play was increased. All these factors resulted in slightly smaller force levels generated from the beta titanium wires in most cases. The results are in agreement with previous investigations, which showed slightly different torque effectiveness between 0.018” x 0.025” β-Ti and SS wires (Daratsianos, 2010).

1.4.1 Sources of error

A major error source is the wire/slot play. The dimensions between wire pieces of the same alloy and cross section varied and as a result, slot play variations between the four appliances influenced the registered values. To minimize random error, repetitions were performed. The OMSS maximum sensor error is 0.3 % in linearity and 1.8 % due to cross talk (Bourauel et al., 1992). Other feasible error sources are the model scanning, the duplication methods and the statistical error of repetitions. Scanning and duplication of stone casts with the use of silicone molds have proven to be precise (Kirschneck et al., 2018; Amuk et al., 2019). Although errors related to human inaccuracy cannot be quantified, all procedures were performed by the same investigator.

1.4.2 Limitations

The clinical transferability of the obtained results should be evaluated in accordance with the limitations of this experimental study. Absence of biological function, i.e. mobility of all teeth of the dental arch due to the presence of periodontal ligament, muscle function and occlusion forces could affect the registered force/moment values. Conflicting results were published regarding lubrication via saliva, friction and the consequent force/moment levels (Thorstenson and Kusy, 2001; Almeida et al., 2019). The experiment was performed with stainless steel ligatures in an effort to reduce friction (Vinay at al., 2014). The use of an idealized experimental situation did not aim to reproduce the force/moment levels and final tooth positions of an orthodontic therapy. The only objective of this study was to compare the selected appliances and treatment protocols with the use of an apparatus able to register forces and moments during 3D representation of orthodontic tooth alignment.

1.5 Abstract

While fully customized lingual bracket systems are becoming a common orthodontic solution, the aim of this study was to examine their force/moment capacity and therapeutic efficacy by comparison with conventional labial appliances. Twenty-four bracket/wire combinations [(bracket appliances: Incognito™, WiN, Discovery® MIM, Discovery® smart), (archwires: 0.012”, 0.014”, 0.016”, 0.016” x 0.022” NiTi, 0.018” x 0.025” β-Ti and 0.018” x 0.025” SS) were tested during simulated alignment and predefined wire activation. Both experimental protocols proved that the combination of rectangular archwires and fully customized lingual appliances increases vertical force levels, regardless of the alloy or cross section. Increased force levels were observed during intrusion/extrusion using 0.016” x 0.022” NiTi, 0.018” x 0.25” SS and 0.018” x 0.025” β-Ti wires. In addition, fully customized lingual appliances generated higher force values, in areas with severe misalignment and smaller interbracket distances in comparison with the conventional labial ones. Regarding the treatment outcome, the simulation resulted in a less rotated premolar when the fully customized lingual appliances were tested. In clinical practice, the orthodontist should

evaluate each case separately in order to adjust the treatment protocol accordingly. A carefully arranged wire sequence, with minimal increase of the subsequent archwires cross-section for every treatment stage, could decrease the force levels produced from the lingual appliances and increase efficiency. Additional orthodontic products, such as elastic chains could be used in order ensure adequate rotation. Archwires of 0.018” x 0.025” should be combined with lingual appliances only when increased anchorage is needed and are highly indicated when a Herbst appliance is utilised for treatment of Class II malocclusion. Direct comparison of 0.018” x 0.025” β-Ti and SS archwires resulted in slight differences. Based on the obtained force values, the two alloys could replace each other in any archwire sequence without influencing the treatment outcome.

1.6 References for the English Summary

Almeida FAC, Almeida APCPSC, Amaral FLB, Basting RT, França FMG, Turssi CP. Lubricating conditions: effects on friction between orthodontic brackets and archwires with different cross-sections. Dental Press J Orthod 2019; 24: 66-72

Amuk NG, Karsli E, Kurt G. Comparison of dental measurements between conventional plaster models, digital models obtained by impression scanning and plaster model scanning. Int Orthod 2019; 17: 151-158

Binhuwaishel L, Al-Jewair T. Lingual Fixed Orthodontic Appliances May Be Associated With More Adverse Effects Than Buccal Appliances. J Evid Based Dent Pract 2018; 18: 349-351

Bock NC, Ruf S, Wiechman D, Jilek T. Herbst plus Lingual versus Herbst plus Labial: a comparison of occlusal outcome and gingival health. Eur J Orthod 2016; 38: 478-484

Bourauel C, Drescher D, Thier M. An experimental apparatus for the simulation of three-dimensional movements in orthodontics. J Biomed Eng 1992; 14: 371-378

Creekmore TD. The importance of interbracket width in orthodontic tooth movement. J Clin Orthod 1976; 10: 530-534

Daratsianos N. Biomechanical analysis of torque capabilities of lingual brackets. Inaugural-Dissertation, Medizinische Fakultät, Rheinische Friedrich-Wilhelms-Universität Bonn, 2010

Doshi UH; Bhad-Patil WA. Static frictional force and surface roughness of various bracket and wire combinations. Am J Orthod Dentofacial Orthop 2011; 139: 74-79

Fidalgo TK, Pithon MM, Maciel JV, Bolognese AM. Friction between different wire bracket combinations in artificial saliva-an in vitro evaluation. J Appl Oral Sci 2011; 19: 57-62

Fuck LM, Wiechmann D, Drescher D. Comparison of the initial orthodontic force systems produced by a new lingual bracket system and a straight-wire appliance. J Orofac Orthop 2005; 66: 363-376

George RD, Hirani S. Fully-customized lingual appliances: how lingual orthodontics became a viable treatment option. J Orthod 2013; 40 Suppl 1: 8-13

Kirschneck C, Kamuf, B, Putsch, C, Chhatwani S, Bizhang M, Danesh G. Conformity, reliability and validity of digital dental models created by clinical intraoral scanning and extraoral plaster model digitization workflows. Comput Biol Med 2018; 100: 114-122

Kusy RP. A review of contemporary archwires: Their properties and characteristics. Angle Orthod 1997; 67; 197-207

Marañón-Vásquez GA, Barreto LSDC, Pithon MM, Nojima LI, Nojima MDCG, Araújo MTS, Souza MMG. Reasons influencing the preferences of prospective patients and orthodontists for different orthodontic appliances. Korean J Orthod 2021; 51: 115-125

Mistakidis I, Katib H, Vasilakos G, Kloukos D, Gkantidis N. Clinical outcomes of lingual orthodontic treatment: a systematic review. Eur J Orthod 2016; 38: 447-458

Montasser MA, Keilig L, Bourauel C. Archwire diameter effect on tooth alignment with different bracket-archwire combinations. Am J Orthod Dentofacial Orthop 2016; 149: 76-83

Moran KI. Relative wire stiffness due to lingual versus labial interbracket distance. Am J Orthod Dentofacial Orthop 1987; 92: 24-32

Mujagic M, Pandis N, Fleming PS, Katsaros C. The Herbst appliance combined with a completely customized lingual appliance: A retrospective cohort study of clinical outcomes using the American Board of Orthodontics Objective Grading System. Int Orthod 2020; 18: 732-738

Papageorgiou SN, Konstantinidis I, Papadopoulou K, Jäger A, Bourauel C. A systematic review and meta-analysis of experimental clinical evidence on initial aligning archwires and archwire sequences. Orthod Craniofac Res 2014; 17: 197-215

Papageorgiou SN, Sifakakis I, Keilig L, Patcas R, Affolter S, Eliades T, Bourauel C. Torque differences according to tooth morphology and bracket placement: a finite element study. Eur J Orthod 2017; 39: 411-418

Pompei-Reynolds RC, Kanavakis G. Interlot variations of transition temperature range and force delivery in copper-nickel-titanium orthodontic wires. Am J Orthod Dentofacial Orthop 2014; 146: 215-226

Proffit WR, Fields Junior HW, Sarver DM. Contemporary Orthodontics. 4th ed. St.Louis: Mosby, 2007; 340, 362

Sifakakis I, Pandis N, Makou M, Eliades T, Katsaros C, Bourauel C. Torque efficiency of different archwires in 0.018- and 0.022-inch conventional brackets. Angle Orthod 2014; 84: 149-154

Sifakakis I, Pandis N, Makou M, Katsaros C, Eliades T, Bourauel C. A comparative assessment of forces and moments generated by lingual and conventional brackets. Eur J Orthod 2013; 35: 82-86

Sridharan K, Sandbhor S, Rajasekaran UB, Sam G, Ramees MM, Abraham EA. An in vitro Evaluation of Friction Characteristics of Conventional Stainless Steel and Self-ligating Stainless Steel Brackets with different Dimensions of Archwires in Various Bracket-archwire Combination. J Contemp Dent Pract 2017; 18: 660-664

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 Orofacial Orthop 2001; 120: 361-370

Vinay K, Venkatesh MJ, Nayak RS, Pasha A, Rajesh M, Kumar P. A comparative study to evaluate the effects of ligation methods on friction in sliding mechanics using 0.022" slot brackets in dry state: An In-vitro study. J Int Oral Health 2014; 6: 76-83

Vu J, Pancherz H, Schwestka-Polly R, Wiechman D. Correction of Class II, Division 2 malocclusions using a completely customized lingual appliance and the Herbst device. J Orofac Orthop 2012; 73: 225–235

Wang Y, Liu C, Jian F, McIntyre GT, Millett DT, Hickman J, Lai W. Initial arch wires used in orthodontic treatment with fixed appliances. Cochrane Database Syst Rev 2018; 7 (7): CD007859

Wiechmann D, Nesbit L. Incognito Clinical Guide. In: Ruedger R, ed, Incognito Clinical Guide. 2nd version. Minessota: 3M Unitek, 2007: 2-1, 2-2

2. Publications

2.1 Publication no. 1

Comparative investigation of fully customized lingual bracket systems and conventional labial appliances: Analysis of forces/moments and final tooth positions

Kyprianou C, Chatzigianni A, Daratsianos N, Bourauel C.

American Journal of Orthodontics and Dentofacial Orthopedics

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American Journal of Orthodontics & Dentofacial Orthopedics

Dear Dr. Kyprianou,

Thank you for revising and resubmitting your manuscript to the AJO-DO. I am now satisfied that all necessary changes have been made and I am pleased to accept your research for publication. Congratulations.

We have tentatively scheduled your article for publication in the Fall of 2022. We understand our wait time for publication is long and we are working to reduce it over the coming year. When we approach the publication date, we will send your article to the production department where it will be prepared for publication. The production department will notify you when the proof is available. Once you approve the proof, the article will be published online ahead of print on the journal website, and it will be printed in an upcoming issue of the journal.

Thank you for submitting your article to the AJO-DO. I look forward to its publication.

With kind regards,

Rolf Behrents
Editor-in-Chief
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Title:

COMPARATIVE INVESTIGATION OF FULLY CUSTOMIZED LINGUAL BRACKET SYSTEMS AND CONVENTIONAL LABIAL APPLIANCES: ANALYSIS OF FORCES/MOMENTS AND FINAL TOOTH POSITIONS

Authors:
Chrystalla Kyprianou[a]
DDS, Doctoral candidate
chrystalla.s.kyprianou@gmail.com

Athina Chatzigianni[b]
DDS, MSc, Dr.med.dent, Special. Orthod, Assistant Professor
achatzigianni@dent.auth.gr

Nikolaos Daratsianos[c]
DDS, MSc Lingual Orthodontics, Dr.med.dent, Special. Orthod, Assistant Professor
nikolaos.daratsianos@uni-bonn.de

Christoph Bourauel[a]
Dipl.-Phys., Dr.rer.nat, Professor
bourauel@uni-bonn.de

a. Department of Oral Medical Technology, School of Dentistry, Faculty of Medicine, University of Bonn, Bonn, Germany, Welschnonnenstr. 17, 53111 Bonn, Germany
b. Department of Orthodontics, Faculty of Dentistry, School of Health Sciences, Aristotle University of Thessaloniki, University Campus, 54124, Thessaloniki, Greece
c. Department of Orthodontics, School of Dentistry, Faculty of Medicine, University of Bonn, Bonn, Germany, Welschnonnenstr.17, 53111 Bonn, Germany

Correspondence to:

Chrystalla Kyprianou
chrystalla.s.kyprianou@gmail.com
Phone number: +4901754572225

Abstract

Introduction: The assessment of forces and moments generated by fully customized lingual appliances and their effectiveness of tooth movement in comparison with conventional labial bracket systems, applied on a specific malocclusion model.

Methods: Two fully customized lingual appliances (Incognito™ and WiN) and two labial bracket systems (Discovery® classic and Discovery® smart) were examined with NiTi wires of different cross sections (0.012", 0.014", 0.016" and 0.016" x 0.022") and three tooth types (canine, lateral incisor and second premolar). Simulated movement was performed, with a wire replacement as soon as forces or moments were no longer effective.

Results: Lingual and labial appliances showed statistically significant differences in initial forces and moments when tested with same cross section wires. Statistically significant differences between the two lingual bracket systems were also registered. Both lingual appliances rotated the premolar less than the conventional labial appliances.

Conclusions: In areas of smaller lingual interbracket distance and higher lingual slot misalignment, the tested lingual multibracket appliances showed higher forces compared to the labial ones. The force difference was particularly prominent with vertically oriented lingual slots and rectangular wires. The tested lingual appliances presented difficulties in rotating the premolar.

Introduction and literature review

In the 70s, Dr. Craven Kurz (California, USA) and Dr. Kinya Fujita (Kanagawa, Japan) invented the first lingual bracket appliances independently [1-3]. A few years later, Dr. Craven Kurz cooperated with a dental company to initiate mass production. Until the early 90s, the initial appliance has undergone several corrections, and other companies embraced the idea of the lingual bracket production [3, 4]. The pick in the evolvement of the lingual braces can be placed in the early 00s when fully customized appliances were introduced using computerized three-dimensional production techniques [5, 6].

Several investigators compared the therapeutic effectiveness of the innovative lingual brackets with the conventional labial bracket systems [7, 8]. Subsequently, some authors have investigated the biomechanical characteristics of fully customized appliances in comparison with pre-adjusted lingual brackets [9, 10].

Although the advantages and disadvantages of the lingual appliances have been addressed in multiple studies, the effectiveness and force/moment capacity of the lingual braces, in general, is still a controversial subject [11-16].

In contrast with previous studies which investigated certain factors under specific circumstances, the purpose of this study was to simulate the alignment procedure of a specific malocclusion model of a selected patient in order to analyze: 1) the levels of initial forces and moments generated from fully customized lingual bracket in comparison with conventional labial appliances at every stage of the alignment procedure, 2) the interaction between the selected bracket systems and a sequence of wires used in everyday orthodontic practice, 3) the effectiveness of the chosen bracket systems in relation to the final position of different tooth types.

Materials and Methods

Bracket appliances

Sixteen bracket/wire combinations were examined with the use of four bracket appliances. Two of the appliances were fully customized lingual bracket systems: 1) Incognito™ lingual brackets (3M Unitek, Monrovia, Minnesota, USA), 2) WiN lingual brackets (DW Lingual Systems, Bad Essen, Germany) and the other two were different types of conventional labial bracket systems: 1) Discovery® classic and 2) Discovery® smart appliances (Dentaurum, Ispringen, Germany). All brackets have a 0.018” slot size. The lingual bracket systems have a vertical slot opening on the incisor and canine brackets, while the premolar/molar lingual brackets and all labial brackets have a horizontal slot opening. The long slot walls were oriented vertically (“ribbonwise”) for the lingual appliances and horizontally (“edgewise”) for the labial appliances (Supplementary Figure 1). The relevant slot widths and distances between the adjacent slots are shown in Supplemental Table 1.

Malocclusion model

An impression of a patient presenting moderate mandibular anterior crowding and bilateral rotation of the premolars (Figure 1) was sent to the certified laboratories in order to construct the lingual appliances incl. a transfer tray, for the indirect bonding. Additionally, the setup model of WiN was scanned and sent to the other certified laboratory of Incognito 3M in order to produce a perfect setup copy (Figure 2). This procedure aimed to create identical setup models and lingual appliances with the same treatment objective.

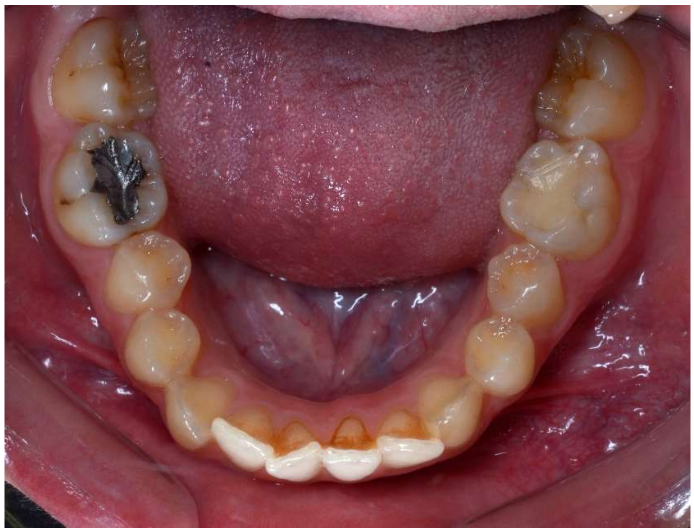


Fig. 1: The lower dental arch of a case with mild crowding.

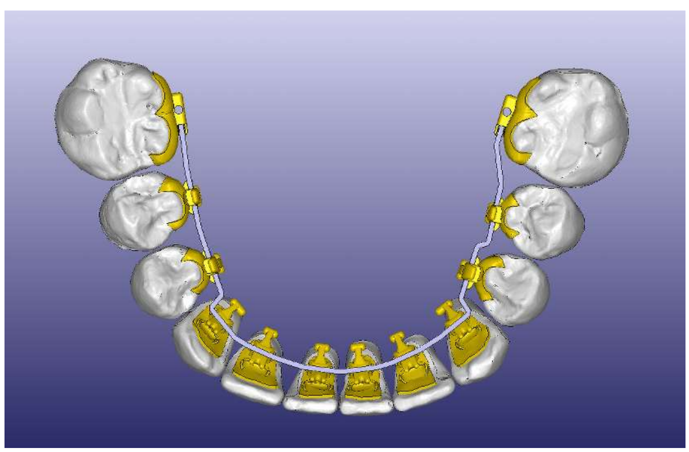


Fig. 2: Digital representation of the setup as received from the Incognito™ laboratory.

Subsequently, resin mandibular models were constructed from the initial malocclusion model. In detail, soft silicone molds of the malocclusion model were prepared to be fulfilled with resin (Technovit® 4004, Kulzer GmbH, Hanau, Germany) and the produced resin casts were modified to fit a self-constructed orthodontic measurement and simulation system (OMSS). Three teeth were examined: the canine of the third quadrant (#33), the lateral incisor (#42) and the second premolar (#45) of the fourth quadrant. Each tooth under examination was removed from the resin cast so it could be replaced with a sensor.

Bonding procedure

The fully customized lingual brackets were bonded indirectly with the use of the customized transfer trays received from the corresponding laboratory, while for the labial brackets, a standard bonding procedure was followed using a 0.018”x0.025” stainless steel wire as a splint, created and adjusted by the same examiner. The stainless steel wire was customized to fit passively in the slots and used for the bonding of the labial appliances at the same position on every resin cast needed for the experimental procedure. The sensor was bonded with the appropriate bracket and adjusted in the OMSS chamber in a position where the slot was parallel to the sensor at the three planes of space: The passive-wire-splint was inserted and ligated on the resin cast and the whole cast/bracket/splint system was secured in a position where no forces were generated on the tooth to be examined. After the adjustment, the splint was removed. The bonding agents were the Transbond™ XT Light Cure adhesive primer and paste (3M Unitek, Monrovia, Minessota, USA) for the labial appliances and the Maximum Cure® sealants A and B (Reliance Orthodontics, Itasca, Illinois, USA) for the lingual appliances.

Archwires

The above-mentioned bracket systems were examined with 0.012”, 0.014”, 0.016” and 0.016”x0.022” nickel titanium (NiTi) wires. For the Incognito™ and WiN lingual appliances, customized archwires were ordered from the corresponding laboratories, along with the customized brackets. The same specifications, i.e. mushroom-shaped wires with straight lateral segments, were ordered for all wire types. Mandibular preformed archwires of the same cross sections (Tensic® ideal arches, Dentaurum, Ispringen, Germany) were used for the labial brackets.

Apparatus

The orthodontic measurement and simulation system (OMSS) [17,18] used for this investigation was constructed following the idea of a two-tooth model described by Burstone and

Koenig[19]. It consists of two 3D force-moment sensors, measuring 3 forces and 3 torques each, which are connected with 3D positioning tables in a temperature-controlled chamber (VEM 03/400, Heraeus Voetsch, Germany). The positioning tables are connected with stepping motors, which allow microstepping in the three planes of space, i.e. each table can perform 3 translations and 3 rotations to mimic orthodontic tooth movement as close to clinical reality as possible. The dimensions and the center of resistance of the tooth under examination are registered prior to the initiation of the simulation process. At first, the 3D sensors detect the forces and moments applied by the tested bracket/wire combination. The software calculates the force-moment vectors on the center of resistance of each tooth and the result is, then, sent to the stepping motors, which move the tooth simulating sensor under examination according to the calculated force and moment by one micro step in the range of 10 micrometers and 0.1 degrees. Then the software calculates the force-moment vectors in the new position and the motors move the sensor by a further step and so on, either for a specific amount of simulated movement steps or until balance is achieved [18]. In so far, the OMSS may be regarded as an electronic typodont, where the wax is replaced by the positioning tables. Similar to a typodont, the tooth under investigation is allowed to react to the applied force system. However, additionally the force system is registered continuously and changes in forces and moments are displayed during the movement.

Thus, this apparatus enables the continuous detection of forces and moments resulting from the tested orthodontic appliance and performs a corresponding simulated tooth movement. The experiment was performed at a constant temperature of 37°C, which resembles the intra-oral temperature.

Each time a new model was to be measured, the system was initialized. Then, the model was mounted to the simulator, while the passive splint or the transfer tray was in place, in order to guarantee that forces and moments were eliminated at the initial position.

Simulation procedure

The first wire of the sequence (0.012” NiTi) was then ligated with Remanium® short, preformed steel ligatures (Dentaurum, Ispringen, Germany) and the simulated movement of the tooth was started. The specific configuration enables only the movement of the tooth under examination, therefore, the wires were ligated only on the sensor and the adjacent teeth, in a way that the wire was fully engaged and could slide in the slot. After the completion of the simulation, i.e. when the simulated motion ended because of achievement of balance, the first wire was removed and replaced with the next of the sequence, at the position from which the previous wire left the tooth, and so on until all wires were examined. The simulation process was performed separately for each tooth under examination and each simulation circle was rerun, five times, with brand new wires and new ligatures each time to verify accuracy. For the WiN appliance, only one set of wires was tested. The wires were removed and religated with new ligatures for each repetition. A resin model, adjusted in the chamber during the simulation process, is shown in Figure 3. The initial force and moment values at the position of the sensor were registered, each time when a new wire was inserted, i.e. for each of the three teeth for four bracket systems with four wires (16 bracket/wire combinations) and five repetitions. The final tooth position after the last wire was tested was also registered.

A)

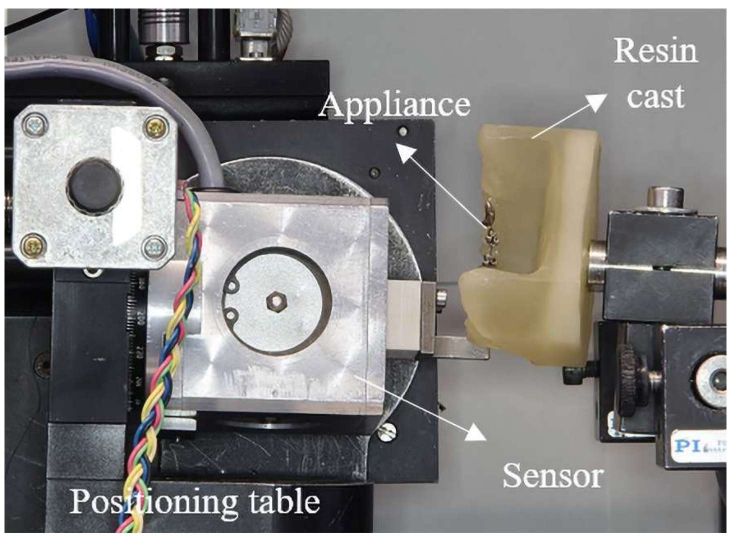


Fig. 3: Resin model adjusted in the OMSS chamber: (A) Apparatus.

B)

Fig. 3: Resin model adjusted in the OMSS chamber: (B) Simulated alignment of the canine (replaced with a sensor) with the use of the Incognito™ appliance.

Statistical analysis

Mean values and standard deviations were calculated for the five repetitions. A Kolmogorov-Smirnov test, with a significance level of 0.01 ($p \leq 0.01$), was used to prove the normal distribution of the data. One-way analysis of variance (ANOVA) procedure was used to identify the influence of the factor “bracket” on the dependant variables “force”, “moment” and “position”. Specifically, one ANOVA was conducted for each wire cross section, each tooth area and each force or moment on a specific axis (i.e. 72 different ANOVAs were conducted). In addition, 18 ANOVAs were conducted to compare the final linear and rotational positions of each tooth on each axis. Post-hoc tests were performed using Student-Newman-Keuls tests. Subsequently, Student’s t-tests for equality of means were used for group comparisons and standard deviations were compared using Levene’s test of equality of variances. For these tests, a significance level of 0.05 ($p \leq 0.05$) was chosen. The whole statistical analysis was performed using the SPSS Statistics software version 9 (IBM, Armonk, New York, USA).

Results

Each axis represents a specific tooth movement, as shown in Table I. Positive or negative signs are adjusted to represent movements of opposite directions, taking into account the opposite bonding surfaces of the labial and lingual brackets on the teeth under examination.

Tab. I: Abbreviations of the registered force/ moment values on the three axes, their definitions and the represented tooth movements.

Abbreviation	Definition	Movement
Fx	Force on the x-axis	(+) Intrusion (-) Extrusion
Fy	Force on the y-axis	Mesiodistal
Fz	Force on the z-axis	(+) Vestibular (-) Oral
Mx	Moment on the x-axis	Rotation
My	Moment on the y-axis	Torque
Mz	Moment on the z-axis	Tipping

Standard deviations typically are in the region of 3-28 % but are not listed in the tables for the sake of clarity. Typical distribution of values can be taken from Figure 4, which also present the median value of the five repetitions. The tables present the mean value of the five repetitions.

Forces (F) and end positions (T) on the y-axis, representing the mesiodistal movement and end positions of the teeth, are not presented due to the specific configuration in which such a movement has no clinical relevance. Thus, 15 ANOVAs (Fy; Table II-V and Ty; Table X) are not presented.

Forces

Initial wires

Forces were registered for all bracket/wire combinations. However, force values generated during the simulated movement with the 0.012-inches wire, which was the initial wire, will be discussed separately. These results are shown in Figure 4 and Table II. Intrusion-extrusion forces ranged between 0.1 N to 2.2 N. The Incognito^{TM} appliance generated

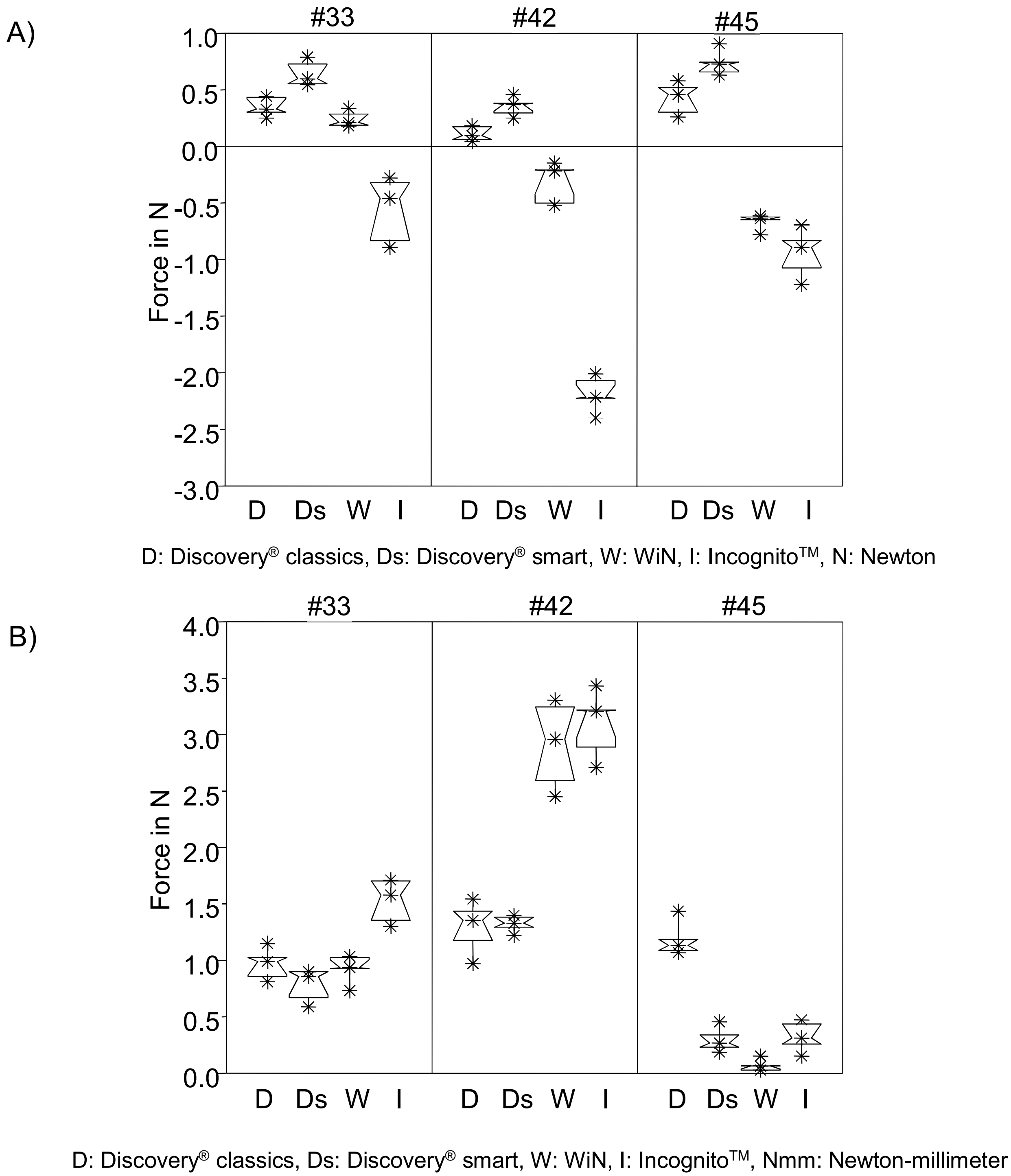


Fig. 4: Force values generated at a specific tooth (canine, lateral incisor, premolar) area by the appliances in combination with the 0.012” wire on: (A) the x-axis/intrusion-extrusion and (B) the z-axis/orovestibular movement.

intrusion-extrusion forces of an opposite direction during the alignment of the lateral incisor and the canine. Orovestibular forces ranged between 0.2 N to 3.1 N. According to ANOVA and Post-hoc tests, during the alignment of the lateral incisor both lingual appliances produced higher orovestibular forces than the labial appliances (Table II; Fz; p=0.000) and the Incognito™ lingual bracket system generated a higher orovestibular force at the canine position in comparison with the rest of the appliances (Table II; Fz; p=0.000). The Discovery® classic appliance generated a force of 1.2 N, which was the highest registered orovestibular force value registered at the premolar area (Table II; Fz; p=0.000).

Tab. II: Force values generated at a specific tooth (canine, lateral incisor, premolar) area, using the four different bracket appliances combined with the 0.012-inch wire.

		Teeth under examination					
		#33		#42		#45	
Brackets	Wires (Inches)	Fx (N)	Fz (N)	Fx (N)	Fz (N)	Fx (N)	Fz (N)
D	0.012	0.4^{a}	1.0^{d}	0.1^{f}	1.3^{j}	0.4^{m}	1.2^{q}
Ds	0.012	0.6^{b}	0.8^{d}	0.4^{g}	1.3^{j}	0.7^{n}	0.3^{r}
W	0.012	0.2^{a}	0.9^{d}	-0.3^{h}	2.9^{k}	-0.7^{p}	0.1^{v}
I	0.012	-0.6^{c}	1.5^{e}	-2.2^{i}	3.1^{k}	-0.9^{p}	0.3^{r}
p value for ANOVA		0.009	0.000	0.000	0.000	0.000	0.000

D: Discovery® classics, Ds: Discovery® smart, W: WiN, I: Incognito™, N: Newton
Fx: Forces generated during the intrusion-extrusion, Fz: Forces generated during the orovestibular movement
$^{a-z}$: Values marked with the same letter do not differ according to Student-Newman-Keuls post -hoc tests.

Subsequent wires

Tables III-V present the mean force values generated during the simulation process with the remaining wires on the x- and z-axes, representing intrusion-extrusion and orovestibular forces, respectively. Forces of different directions were registered between the four bracket appliances at the same stages of the simulation process. Statistical analysis showed that, orovestibular forces generated from the fully customized lingual appliances at the lateral incisor area were larger in comparison with those generated from labial bracket systems during the whole simulation process (Table II; Fz; p=0.000, Table III; Fz; p=0.000, Table IV; Fz; p=0.012, Table V; Fz; p=0.028). Particularly, the highest force value for the lingual appliances was 3.1 N, while labial appliances produced values lower than

1.3 N. Also, forces generated from the lingual appliances at the intrusion extrusion direction were higher than forces generated from the labial systems when combined with the rectangular wire at the canine area (Table V; Fx; p=0.001).

Tab. III: Force values generated at a specific tooth (canine, lateral incisor, premolar) area, using the four different bracket appliances combined with the 0.014-inch wire.

		Teeth under examination					
		#33		#42		#45	
Brackets	Wires (Inches)	Fx (N)	Fz (N)	Fx (N)	Fz (N)	Fx (N)	Fz (N)
D	0.014	0.4^{a}	0.6^{c}	-0.2^{e}	0.9^{g}	0.6^{k}	1.1^{p}
Ds	0.014	0.4^{a}	0.4^{c}	-0.1^{e}	0.9^{g}	0.5^{k}	0.3^{r}
W	0.014	-0.4^{b}	0.9^{c}	-0.4^{e}	2.4^{h}	0.5^{k}	0.4^{r}
I	0.014	-0.9^{b}	1.6^{d}	-1.0^{f}	3.0^{h}	0.4^{k}	0.8^{p}
p value for ANOVA		0.042	0.001	0.001	0.000	0.308	0.000

D: Discovery® classics, Ds: Discovery® smart, W: WiN, I: Incognito™, N: Newton
Fx: Forces generated during the intrusion-extrusion, Fz: Forces generated during the orovestibular movement
a-z: Values marked with the same letter do not differ according to Student-Newman-Keuls post -hoc tests.

Tab. IV: Force values generated at a specific tooth (canine, lateral incisor, premolar) area, using the four different bracket appliances combined with the 0.016-inch wire.

		Teeth under examination					
		#33		#42		#45	
Brackets	Wires (Inches)	Fx (N)	Fz (N)	Fx (N)	Fz (N)	Fx (N)	Fz (N)
D	0.016	0.4^{a}	$0.3^{c,d}$	$-0.3^{f,g}$	0.9^{j}	0.6^{k}	0.3^{m}
Ds	0.016	0.2^{a}	0.2^{c}	$-0.3^{f,g}$	0.9^{j}	0.6^{k}	0.4^{m}
W	0.016	0.3^{a}	0.5^{d}	-0.2^{f}	1.7^{h}	-0.2^{r}	0.3^{m}
I	0.016	0.6^{a}	1.7^{e}	-0.7^{g}	1.6^{h}	-0.3^{r}	0.5^{m}
p value for ANOVA		0.275	0.000	0.034	0.012	0.001	0.071

D: Discovery® classics, Ds: Discovery® smart, W: WiN, I: Incognito™, N: Newton
Fx: Forces generated during the intrusion-extrusion, Fz: Forces generated during the orovestibular movement
a-z: Values marked with the same letter do not differ according to Student-Newman-Keuls post -hoc tests.

Tab. V: Force values generated at a specific tooth (canine, lateral incisor, premolar) area, using the four different bracket appliances combined with the 0.016 x 0.022-inch wire.

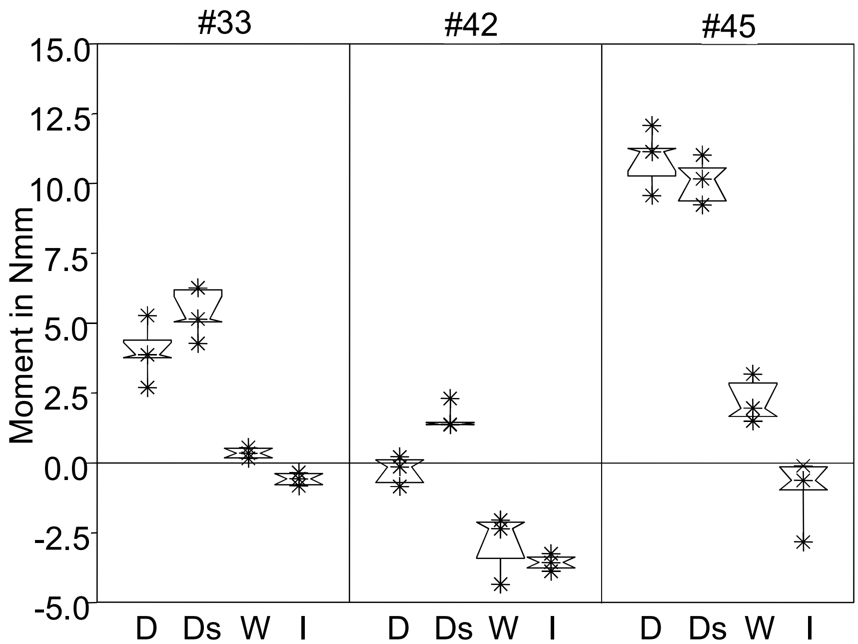
		Teeth under examination					
		#33		#42		#45	
Brackets	Wires (Inches)	Fx (N)	Fz (N)	Fx (N)	Fz (N)	Fx (N)	Fz (N)
D	0.016x0.022	0.2[a]	1.0[d]	-0.8[f]	-0.4[g]	0.4[k]	1.8[p]
Ds	0.016x0.022	-0.2[c]	0.9[d]	-0.3[f]	-0.1[g]	0.5[k]	2.0[p]
W	0.016x0.022	-3.4[b]	1.0[d]	-0.9[f]	1.7[h]	0.4[k]	0.5[r]
I	0.016x0.022	-4.1[b]	1.1[d]	-1.0[f]	1.2[h]	0.4[k]	1.2[p]
p value for ANOVA		0.001	0.560	0.087	0.028	0.695	0.001

D: Discovery® classics, Ds: Discovery® smart, W: WiN, I: Incognito™, N: Newton
Fx: Forces generated during the intrusion-extrusion, Fz: Forces generated during the orovestibular movement
[a-z]: Values marked with the same letter do not differ according to Student-Newman-Keuls post -hoc tests.

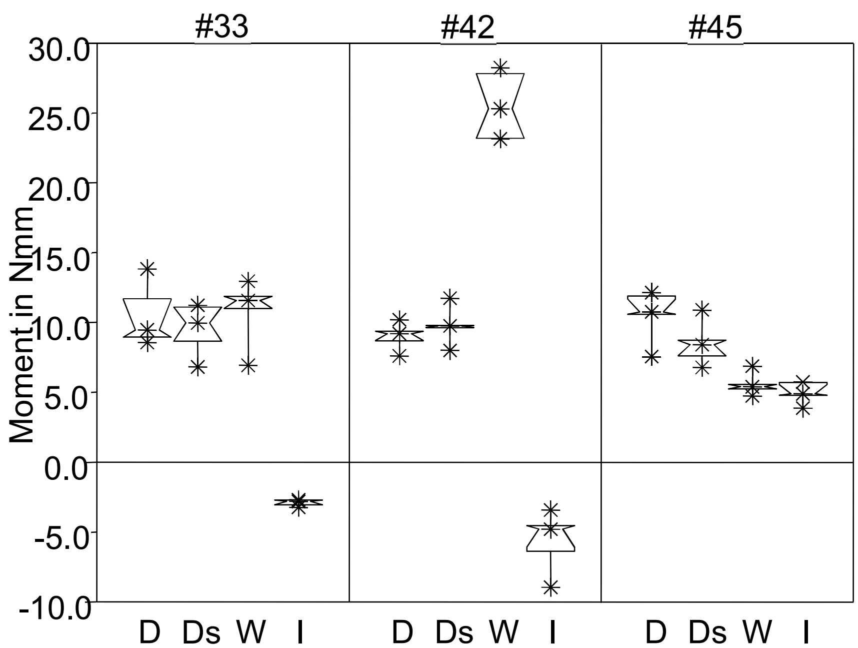
Moments

Initial wires

The moments registered during the simulation of the alignment with the 0.12-inch wires are shown in Figure 5 and in Table VI. Both lingual appliances generated statistically higher moments during the mesiodistal rotation of the lateral incisor on the x-axis (Table VI; Mx; p=0.000). During the alignment of the canine, the Incognito™ appliance generated a statistically higher moment (tipping) (Table VI; Mz; p=0.006) or moments of the opposite direction (rotation and torque) in comparison with the rest of the appliances. The Win lingual appliance produced a statistically higher torque value at the lateral incisor area (Table VI; My; p=0.000) and a lower value during the rotation of the canine (Table VI; Mx; p= 0.000) compared to the labial appliances. In addition, ANOVA proved that, moments generated from the lingual appliances at the premolar area differed from those generated from the labial appliances (Table VI; p=0.000). This variation is easily observed on the three axes, where labial appliances generated a maximum mean value of 10.9 Nmm while customized lingual appliances produced a maximum moment 5.6 Nmm. Regarding the tipping of the second premolar, lingual appliances generated values of no more than 1.1 Nmm.



D: Discovery® classics, Ds: Discovery® smart, W: WiN, I: Incognito™, Nmm: Newton-millimeter



D: Discovery® classics, Ds: Discovery® smart, W: WiN, I: Incognito™, Nmm: Newton-millimeter

Fig. 5: Moment values generated at a specific tooth (canine, lateral incisor, premolar) area by the appliances in combination with the 0.012” wire on: (A) the x-axis/rotation, (B) the y-axis/torque, (C) the z-axis/tipping.

Subsequent wires

The moment values registered during the simulated movement with the rest of the wires are shown in Tables VII-IX. Moments of different directions were registered between the four bracket systems on the same axes during the simulation process. Statistically significant differences were observed between the moments generated from the Incognito™ appliance and those produced by the rest of the appliances at the canine and lateral incisor area. According to Post-hoc tests, torque values produced by the Win bracket system at the lateral incisor area were, in general, higher than those generated from the labial appliances. Also, Win produced statistically lower rotational values during the alignment of the canine with the use of the 0.014 (M_x=1.0 Nmm) and 0.016-inch (M_x=1.4 Nmm) wires. At the premolar area, fully customized lingual appliances generated lower moment values on the three axes, although in some cases the differences were not statistically significant (Table VIII; M_x; p= 0.107, Table IX; M_x; p=0.230).

Tab. VI: Moment values generated at a specific tooth (canine, lateral incisor, premolar) area, using the four different bracket appliances combined with the 0.012-inch wire.

		Teeth under examination								
		#33			#42			#45		
Brackets	Wires (Inches)	Mx (Nmm)	My (Nmm)	Mz (Nmm)	Mx (Nmm)	My (Nmm)	Mz (Nmm)	Mx (Nmm)	My (Nmm)	Mz (Nmm)
D	0.012	4.0^{b}	10.3^{e}	-4.3^{h}	-0.4^{m}	9.0^{p}	-7.8^{r}	10.9^{v}	10.6^{y}	3.6^{i}
Ds	0.012	5.4^{c}	9.6^{e}	-3.5^{h}	1.6^{j}	9.8^{p}	-8.7^{r}	10.1^{v}	8.5^{w}	4.9^{i}
W	0.012	0.4^{a}	10.9^{e}	-5.9^{h}	-2.8^{k}	25.5^{n}	-7.6^{r}	2.2^{u}	5.6^{x}	1.1^{z}
I	0.012	-0.6^{d}	-2.9^{f}	-10.0^{g}	-3.6^{k}	-5.6^{q}	-23.1^{s}	-0.9^{t}	5.0^{x}	0.8^{z}
p value for ANOVA		0.000	0.000	0.006	0.000	0.000	0.000	0.000	0.000	0.000

D: Discovery® classics, Ds: Discovery® smart, W: WiN, I: Incognito™, Nmm: Newton-millimeter

Mx: Momenтs generated during the rotation of the tooth around its long axis, My: Moments generated during torque application, Mz: Moments generated during tipping

$^{a-z}$: Values marked with the same letter do not differ according to Student-Newman-Keuls post -hoc tests.

Tab. VII: Moment values generated at a specific tooth (canine, lateral incisor, premolar) area, using the four different bracket appliances combined with the 0.014-inch wire.

		Teeth under examination								
		#33			#42			#45		
Brackets	Wires (Inches)	Mx (Nmm)	My (Nmm)	Mz (Nmm)	Mx (Nmm)	My (Nmm)	Mz (Nmm)	Mx (Nmm)	My (Nmm)	Mz (Nmm)
D	0.014	3.6^{b}	$7.7^{d,e}$	-5.2^{g}	-1.0^{j}	5.3^{m}	$-7.0^{s,r}$	6.9^{t}	10.7^{v}	-8.1^{z}
Ds	0.014	5.0^{b}	4.4^{d}	-5.4^{g}	-0.6^{j}	6.1^{m}	-3.9^{s}	5.3^{t}	6.0^{w}	-5.2^{y}
W	0.014	1.0^{a}	11.5^{e}	-7.9^{g}	-3.1^{k}	21.5^{n}	-8.7^{r}	0.6^{u}	4.3^{w}	-2.6^{x}
I	0.014	-5.0^{c}	-1.6^{f}	-12.7^{h}	$-2.1^{j,k}$	-8.8^{p}	-21.4^{q}	1.3^{u}	2.7^{w}	$-4.1^{x,y}$
p value for ANOVA		0.000	0.002	0.009	0.004	0.001	0.000	0.000	0.000	0.000

D: Discovery® classics, Ds: Discovery® smart, W: WiN, I: Incognito™, Nmm: Newton-millimeter

Mx: Momenтs generated during the rotation of the tooth around its long axis, My: Moments generated during torque application, Mz: Moments generated during tipping

$^{a-z}$: Values marked with the same letter do not differ according to Student-Newman-Keuls post -hoc tests.

Tab. VIII: Moment values generated at a specific tooth (canine, lateral incisor, premolar) area, using the four different bracket appliances combined with the 0.016-inch wire.

		Teeth under examination								
		#33			#42			#45		
Brackets	Wires (Inches)	Mx (Nmm)	My (Nmm)	Mz (Nmm)	Mx (Nmm)	My (Nmm)	Mz (Nmm)	Mx (Nmm)	My (Nmm)	Mz (Nmm)
D	0.016	2.8^{a}	3.7^{e}	-4.2^{f}	-2.8^{h,j}	4.4^{k}	-4.2^{p}	2.9^{r}	4.7^{t}	-11.0^{z}
Ds	0.016	5.3^{b}	1.7^{e}	-2.2^{f}	-0.4^{h}	4.2^{k}	2.2^{s}	3.0^{r}	8.0^{u}	-12.4^{z}
W	0.016	1.4^{a}	5.4^{e}	-5.9^{f}	-4.9^{j}	14.5^{m}	-4.9^{p}	1.0^{r}	1.6^{s}	-2.5^{x}
I	0.016	-4.2^{c}	-0.6^{d}	-12.2^{g}	-3.9^{j}	-2.0^{n}	-12.2^{q}	1.5^{r}	-2.0^{w}	-3.8^{x}
p value for ANOVA		0.002	0.018	0.000	0.008	0.000	0.001	0.107	0.000	0.000

D: Discovery® classics, Ds: Discovery® smart, W: WiN, I: Incognito™, Nmm: Newton-millimeter

Mx: Momenтs generated during the rotation of the tooth around its long axis, My: Moments generated during torque application, Mz: Moments generated during tipping

a-z: Values marked with the same letter do not differ according to Student-Newman-Keuls post -hoc tests.

Tab. IX: Moment values generated at a specific tooth (canine, lateral incisor, premolar) area, using the four different bracket appliances combined with the 0.016 x 0.022-inch wire.

		Teeth under examination								
		#33			#42			#45		
Brackets	Wires (Inches)	Mx (Nmm)	My (Nmm)	Mz (Nmm)	Mx (Nmm)	My (Nmm)	Mz (Nmm)	Mx (Nmm)	My (Nmm)	Mz (Nmm)
D	0.016x0.022	4.9^{a}	6.9^{c}	-5.7^{e}	-2.0^{g}	2.9^{j}	2.4^{m}	5.1^{p}	11.3^{r}	-8.2^{v}
Ds	0.016x0.022	5.6^{a}	7.9^{c}	-1.4^{e}	-2.2^{g}	3.4^{j}	7.2^{m}	5.0^{p}	24.5^{s}	-16.2^{v}
W	0.016x0.022	1.8^{a}	23.7^{d}	-17.3^{f}	-6.0^{h}	16.1^{k}	4.4^{m}	3.4^{p}	3.8^{r}	-11.2^{v}
I	0.016x0.022	-4.0^{b}	16.1^{c,d}	-17.4^{f}	-1.5^{g}	3.9^{j}	8.3^{m}	3.0^{p}	3.3^{r}	-15.9^{v}
p value for ANOVA		0.109	0.012	0.000	0.003	0.020	0.114	0.230	0.000	0.276

D: Discovery® classics, Ds: Discovery® smart, W: WiN, I: Incognito™, Nmm: Newton-millimeter

Mx: Momenтs generated during the rotation of the tooth around its long axis, My: Moments generated during torque application, Mz: Moments generated during tipping

a-z: Values marked with the same letter do not differ according to Student-Newman-Keuls post -hoc tests.

Final positions

At the end of the simulated alignment of the teeth under examination with the specific bracket/wire combinations, the final positions of the three teeth were registered. Several statistical differences were recorded between the four bracket types. According to ANOVA, the canine was directed to different rotational positions by the four appliances (Table XI; Rx; p=0.000). The simulation with the Discovery® classic resulted in a rotation of 5.0°, with the Discovery® smart in a rotation of 11.7°, with the Win in a rotation of 2.0° and with the Incognito™ in a rotation of -7.8°. Moreover, the Incognito™ appliance directed the canine in a different direction on the intrusion-extrusion axis, while at the lateral incisor area a torque of the opposite direction was generated by the same appliance. Furthermore, both lingual bracket systems rotated the premolar on a different (less rotated) position in comparison with the labial appliances (Table XI; Rx; p=0.000). The differences ranged between 5 and 9.1°, depending on which appliances are compared. Also, a difference of 3.6° was observed between the two labial bracket systems. The final rotational position of the premolar on the specific axis is shown in Table 4. The orovestibular position of the second premolar differed statistically between the simulated movement with the labial and lingual bracket systems (Table X; Tz; p=0.000). Fully customized lingual appliances guided the specific tooth more vestibulary, however, differences were also observed between the two labial appliances. The final positions of the three teeth are shown in Table 4.

Tab. X: The final linear positions of the canine, the lateral incisor and the premolar in relation to the four appliances.

	Teeth under examination					
	#33		#42		#45	
Brackets	Tx (mm)	Tz (mm)	Tx (mm)	Tz (mm)	Tx (mm)	Tz (mm)
D	0.3^{a}	0.5^{e}	-0.1^{g}	1.4^{m}	1.2^{r}	1.4^{s}
Ds	0.6^{b}	0.3^{f}	0.1^{h}	1.3^{m}	1.1^{r}	0.9^{t}
W	0.2^{c}	0.5^{e}	0.2^{k}	1.2^{m}	1.1^{r}	1.9^{v}
I	-0.7^{d}	0.6^{e}	-0.1^{g}	1.2^{m}	1.1^{r}	1.8^{v}
p value for ANOVA	0.000	0.002	0.000	0.418	0.000	0.000

D:Discovery® classics, Ds: Discovery® smart, W: WiN, I: Incognito™
Tx: Position of the tooth on the x-axis (amount of intrusion-extrusion) in millimeters, Tz: Position of the tooth on the z-axis (amount of orovestibular movement) in millimeters
a-z: Values marked with the same letter do not differ according to Student-Newman-Keuls post -hoc tests

Tab. XI: The final rotational positions of the canine, the lateral incisor and the premolar in relation to the four appliances.

	Teeth under examination								
	#33			#42			#45		
Brackets	Rx (degrees)	Ry (degrees)	Rz (degrees)	Rx (degrees)	Ry (degrees)	Rz (degrees)	Rx (degrees)	Ry (degrees)	Rz (degrees)
D	5.0[a]	2.0[d]	1.8[f]	-5.3[h]	3.9[k]	-1.9[p]	7.3[q]	5.8[t]	-11.5[x]
Ds	11.7[b]	1.1[d]	2.4[f]	-4.3[h]	3.7[k]	-1.7[p]	10.9[r]	4.4[v]	-10.9[x]
W	2.0[c]	1.8[d]	1.6[f]	-4.3[h]	4.5[k]	-2.9[p]	1.8[s]	6.4[t]	-9.1[x]
I	-7.8[d]	-1.7[e]	-7.6[g]	-0.3[j]	-5.3[m]	-2.6[p]	2.3[s]	2.6[w]	-5.4[y]
p value for ANOVA	0.000	0.000	0.003	0.001	0.000	0.460	0.000	0.000	0.000

D: Discovery® classics, Ds: Discovery® smart, W: WiN, I: Incognito™

Mx: Rotational position of the tooth on the x-axis (amount of rotation around the long axis of the tooth) in degrees, My: Rotational position of the tooth on the y-axis (amount of torque) in degrees, Mz: Rotational position of the tooth on the z-axis (amount of tipping) in degrees

[a-z]: Values marked with the same letter do not differ according to Student-Newman-Keuls post -hoc tests.

Discussion

The malocclusion model selected represents a classic crowded mandibular case. The replaced teeth selection was made based on the tooth type and the severity of the malocclusion of the teeth. Three different types of teeth with different inclinations and positions were selected. The positioning of the brackets, the bonding procedure as well as, the ligation of the wires, were performed from the same investigator for better reproducibility.

As for any in-vitro study, the clinical transferability of the registered data should be taken into account. In a classical typodont, tooth movement can be simulated by soft wax, allowing the teeth to move as a reaction to the applied force systems. In the OMSS, the wax is replaced by the force/torque transducers, the positioning tables and the control program, calculating tooth movements from the applied force systems based on the concept of a center of resistance. In so far, the OMSS allows a 3D representation of orthodontic tooth movements of single teeth, with the benefit of continuously registering the varying force systems during the movement. The 3D maneuverability and the registration of all three forces and three torques per tooth under investigation, allows the comparison of different treatment protocols and/or orthodontic appliances.

Although, several statistically significant differences were recorded between the four bracket systems, only a few of them have clinical significance. Variances of a few micrometers may be highlighted as statistically significant, but such dissimilarities are very likely to occur in everyday practice and do not affect the overall treatment outcome.

Force and moment values varied between the five repetitions with the same type of wire. This observation confirms previous studies that investigated the effect of manufacturing errors or deviations during the wire production process. Wires of the same alloy and cross section, manufactured by the same company, could generate diverse force/moment values[20,21]. A further factor might be the differences between the contact status of wires and brackets resulting from the consecutive wire insertions and sensor adjustments, which is a typical measurement error.

Due to the reduced free wire length and the increased wire stiffness at the anterior region, which are caused by the morphology of the lingual bracket systems, the forces and moments generated from the lingual bracket systems were expected to be higher than those produced from the labial appliances[22-25].

In this study, the use of a 0.012” wire combined with fully customized lingual appliances resulted in higher force/moment values during the orovestibular and the rotational movement of the lateral incisor compared to the forces generated from the labial appliances. The interbracket distances between the lateral incisor and the neighboring teeth were considerably smaller for the fully customized lingual appliances. With the use of the same wire, the Incognito appliance generated similar forces to the labial bracket systems in many cases nevertheless, this appliance generated higher forces and moments of a different direction during the simulated alignment of the canine and the lateral incisor. These results have a clear correlation with the divergence of the final positions of these teeth. Taking all the factors into account, we could assume that there was a differentiation on the transfer tray or the wire morphology of the Incognito™ appliance, which resulted in varying final positions. Also, the Win appliance generated initial forces similar to the labial bracket systems in most cases apart from the orovestibular movement of the lateral incisor. More differences were observed between the two lingual systems and between the lingual and the labial bracket systems in relation to the moment values.

According to Post-hoc tests, the initial forces between the two lingual brands do not vary, excluding the cases in which the Incognito appliance generated forces of an opposite direction for reasons already explained above. Slight differences could result from inconsistent ligation pressure and unalike wire adjustment. Those differentiations were awaited and could not be avoided during the experiment the same way they cannot be controlled in vivo.

Regarding forces and moments generated from the rest of the wires of the sequence, the values documented for each wire are significantly affected by the amount of tooth movement achieved from the previous wire. Consequently, larger variations of values and directions of forces and moments on the same axis were awaited. At the canine area, lingual bracket appliances generated larger vertical forces when combined with the rectangular wire, whereas during the alignment procedure with the previous wires, such big differences were not observed. Obviously, the force difference results from the amount of residual misalignment of the slot walls, which was relatively small with 42 and 45 – those teeth showed no statistically significant vertical force difference. However, the force difference also depends on the variable wire orientation: The wire was placed with the higher dimension vertically oriented in the lingual appliances, creating higher vertical forces if the teeth were misaligned enough, like 33. In clinical practice, an additional wire could have been used between the 0.016” NiTi wire and the rectangular wire to reduce force values. Alternatively, a rectangular wire with smaller dimensions could be used as finishing wire. At the lateral incisor area, orovestibular forces generated from the lingual appliances were higher during the whole simulation. The small interbracket distance and the position of the specific tooth were the reasons for these observations.

The Win appliance produced lower moment values during the rotation of the canine around the x-axis. The difference, between the moment value generated from the appliance when combined with the rectangular wire and the labial bracket systems, was not statistically significant. Due to the lower moment values, the Win appliance rotated the canine less than the labial appliances. However, divergence was observed between the two labial appliances too.

Lingual appliances presented difficulties to rotate the second premolar. This investigation was performed with the use of customized archwires with straight lateral segments. As a result, the alignment of the premolar was simulated with the use of straight wires for both labial and lingual bracket systems. Due to the morphology of the setup as presented in Figure 2, side effects normally expected from the combination of straight lateral segments with lingual appliances (i.e. oral movement of the premolars) were not observed in this study. In clinical practice the use of customized lateral segments in combination with the mobility of the adjacent teeth could result to a slightly different position of the premolar. Additionally, for the rotation to be achieved in full range, an elastic chain reinforcement technique could be used clinically. In the Incognito™ appliance system clinical guide[26], the conventional lasso technique is suggested for cases in which a large amount of rotation is needed. This phenomenon and the discrepancies observed during the alignment with the Incognito appliance were the only cases in which the differences between the registered final positions have clinical significance. In all the other cases, the labial and lingual bracket systems guided the teeth under examination to similar final positions.

The limitations of this study were: 1) the use of an idealized experimental situation (simulation device) without periodontal ligament, mobility of the adjacent teeth, occlusion and saliva, 2) the use of steel ligatures. The absence of the above-mentioned biological factors can result to different force/moment levels, as well as different final tooth positions. Thus, this experimental protocol aims to compare the efficacy of the selected appliances and not to reproduce a realistic orthodontic therapy. Regarding saliva, previous studies showed controversial results regarding the influence of lubrication on friction and the consequent orthodontic forces[28,29]. The use of steel ligatures results in less friction compared to elastic ligatures[27] however, the latter are more commonly used in labial and lingual multibracket technique, although they generate higher friction. The choice to use them and ligate only two adjacent teeth at a time, was mainly driven by the fact that only one tooth moves in the test set-up, which would have been impossible with increased friction. Also, the fully customized lingual appliances were constructed on a VTO setup model while the labial appliances were not customized. This fact results in different treatment objectives between the appliances under examination, however, this is more or less standard clinical procedure in private orthodontic practice and this study aimed to investigate this exact situation. The lack of occlusion and mobility of the neighboring teeth should also result in different movement and final positions of the simulated teeth.

Conclusions

1. During the simulated orovestibular movement of the lower lateral incisor, the fully customized lingual appliances of this study generated higher forces compared to the labial appliances due to higher lingual slot misalignment and smaller lingual interbracket distance.
2. The lingual appliances generated higher vertical force values when combined with a rectangular wire, as the latter was – in contrast to the labial brackets – vertically oriented. This was the case only for the lower canine, as the residual misalignment of the neighboring slots, after correction from the previous wires, was still evident.
3. The clinician should carefully study the patient teeth with the brackets in situ, search for high adjacent slot misalignment and small interbracket distances, and if force reduction is desirable, use extended wire sequences with smaller cross sections.

4. Regarding the moment values, no safe conclusion can be extracted from the comparison between labial and fully customized lingual appliances.
5. Final positions were the same in most cases. Lingual appliances presented difficulties in rotating the premolar using the specific wire sequence. In clinical practice a wire alternative methods i.e: chain reinforcement could be used.

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References

1. Kurz C, Swartz ML, Andreiko C. Lingual orthodontics: a status report. Part 2: Research and development. J Clin Orthod 1982;16:735-40.
2. Fujita K. Development of lingual bracket technique. Esthetic and hygienic approach to orthodontic treatment. Part 1. Background and design. Shika Rikogaku Zasshi 1978;19:81-86.
3. Chatoo A. A view from behind: a history of lingual orthodontics. J Orthod 2013;40 Suppl 1:2-7.
4. Creekmore T. Lingual orthodontics-its renaissance. Am J Orthod Dentofacial Orthop 1989;96:120-137.
5. Wiechmann D. A new bracket system for lingual orthodontic treatment. Part 1: Theoretical background and development. J Orofac Orthop 2002;63:234-245.

6. Wiechmann D, Rummel V, Thalheim A, Simon VS, Wiechmann L. Customized bracket and archwires for lingual orthodontic treatment. Am J Orthod Dentofacial Orthop 2003;124:593–599.

7. Papageorgiou SN, Gölz L, Jäger A, Eliades T, Bourauel C. Lingual vs. labial fixed orthodontic appliances: systematic review and meta-analysis of treatment effects. Eur J Oral Sci 2016;124:105-118.

8. Ata-Ali F, Cobo T, De Carlos F, Cobo J, Ata-Ali J. Are there differences in treatment effects between labial and lingual fixed orthodontic appliances? A systematic review and meta-analysis. BMC Oral Health 2017;17:133.

9. Choi S, Kim JH, Kim NJ, Lee SH, Kim H, Kim KA, Park KH, Park YG. Morphological investigation of various orthodontic lingual bracket slots using scanning electron microscopy and atomic force microscopy. Microsc Res Tech 2016;79:1193-1199.

10. Daratsianos N, Bourauel C, Fimmers R, Jäger A, Schwestka-Polly R. In vitro biomechanical analysis of torque capabilities of various 0.018″ lingual bracket-wire systems: total torque play and slot size. Eur J Orthod 2016;38:459-469.

11. George RD, Hirani S. Fully-customized lingual appliances: how lingual orthodontics became a viable treatment option. J Orthod 2013;40 Suppl 1:S8-13.

12. Alobeid A, El-Bialy T, Reimann S, Keilig L, Cornelius D, Jäger A, Bourauel C. Comparison of the efficacy of tooth alignment among lingual and labial brackets: an in vitro study. Eur J Orthod 2018;40:660-665.

13. Sifakakis I, Pandis N, Makou M, Eliades T, Katsaros C Bourauel C. A comparative assessment of torque generated by lingual and conventional brackets. Eur J Orthod 2013;35:375-380.

14. Lombardo L, Scuzzo G, Arreghini A, Gorgun O, Ortan YO, Siciliani G. 3D FEM comparison of lingual and labial orthodontics in en masse retraction. Prog Orthod 2014;15:38.

15. Grauer D, Proffit WR. Accuracy in tooth positioning with a fully customized lingual orthodontic appliance. Am J Orthod Dentofacial Orthop 2011;140:433-443.

16. Fuck LM, Wiechmann D, Drescher D. Comparison of the initial orthodontic force systems produced by a new lingual bracket system and a straight-wire appliance. J Orofac Orthop 2005;66:363-376.

17. Drescher D, Bourauel C, Thier M. Application of the orthodontic measurement and simulation system (OMSS) in orthodontics. Eur J Orthod 1991;13:169-178.

18. Bourauel C, Drescher D, Thier M. An experimental apparatus for the simulation of three-dimensional movements in orthodontics. J Biomed Eng 1992;14:371-378.

19. Burstone CJ, Koenig HA. Force systems from an ideal arch. Am J Orthod 1974;65:270-289

20. Pompei-Reynolds RC, Kanavakis G. Interlot variations of transition temperature range and force delivery in copper-nickel-titanium orthodontic wires. Am J Orthod Dentofacial Orthop 2014;146:215-226.

21. 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;70:285-296.

22. Creekmore TD. The importance of interbracket width in orthodontic tooth movement. J Clin Orthod 1976;10:530-534

23. Moran KI. Relative wire stiffness due to lingual versus labial interbracket distance. Am J Orthod Dentofacial Orthop 1987;92:24-32.

24. Sifakakis I, Pandis N, Makou M, Katsaros C, Eliades T, Bourauel C. A comparative assessment of forces and moments generated by lingual and conventional brackets. Eur J Orthod 2013;35:82-86.

25. Alobeid A, El-Bialy T, Khawatmi S, Dirk C, Jäger A, Bourauel C. Comparison of the force levels among labial and lingual self-ligating and conventional brackets in simulated misaligned teeth. Eur J Orthod 2017;39:419–425.

26. Wiechmann D, Nesbit L. Incognito Clinical Guide. In: Ruedger R, editor, Incognito Clinical Guide. 2nd version. Minessota:3M Unitek; 2007. p. 2-1, 2-2.

27. Vinay K, Venkatesh MJ, Nayak RS, Pasha A, Rajesh M, Kumar P. A comparative study to evaluate the effects of ligation methods on friction in sliding mechanics

using 0.022" slot brackets in dry state: An In-vitro study. J Int Oral Health 2014; 6:76-83.

28. 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 Orofacial Orthop 2001;120:361-370.

29. Phukaoluan A, Khantachawana A, Kaewtatip P, Dechkunakorn S, Anuwongnukroh N, Santiwong P, Kajornchaiyakul J. Comparison of friction forces between stainless orthodontic steel brackets and TiNi wires in wet and dry conditions. Int Orthod 2017;15:13-24.

Supplementary Material

Supplemental Tab. 1: Slot widths and interbracket distances of the four appliances. All distances were measured on the resin casts with the use of an electronic caliper (Mitutoyo Digimatic 500-120, Mitutoyo Deutschland GmbH, Neuss, Germany).

	Slot widths			
	Discovery classics	Discovery smart	Incog-nito	WiN
Lower left 1st bicuspid (#34)	3.3	2.7	2.5	3.1
Lower left cuspid (#33)	2.9	2.7	2.3	2.5
Lower left lateral incisor (#32)	2.6	2.3	2.4	2.1
Lower right central incisor (#41)	2.6	2.3	2.4	2.1
Lower right lateral incisor (#42)	2.6	2.3	2.4	2.1
Lower right cuspid (#43)	3.0	2.7	2.4	2.5
Lower right 1st bicuspid (#44)	3.3	2.8	2.4	3.0
Lower right 2nd bicuspid (#45)	3.3	2.7	2.4	3.1
Lower right 1st molar (#46)	3.2	3.2	3.9	3.1
	Distance between adjacent slots			
	Discovery classics	Discovery smart	Incog-nito	WiN
#34-#33	2.9	3.6	3.7	3.4
#33-#32	4.3	5.1	2.0	2.0
#41-#42	4.1	5.0	1.3	1.2
#42-#43	4.8	5.1	2.3	2.2
#44-#45	2.0	2.3	5.7	5.2
#45-#46	6.7	7.4	4.4	4.4

(A)

(B)

Supplementary Fig. 1: Slot shapes of (A) the fully customized lingual and (B) the labial appliances.

2.1 Publication no. 2

Vertical and Orovestibular Forces Generated by Beta-Titanium and Stainless-Steel Rectangular Wires in Labial and Fully Customized Lingual Bracket Systems

Kyprianou C, Chatzigianni A, Daratsianos N, Bourauel C.

Materials

materials

MDPI

Article

Vertical and Orovestibular Forces Generated by Beta-Titanium and Stainless-Steel Rectangular Wires in Labial and Fully Customized Lingual Bracket Systems

Chrystalla Kyprianou [1,*], Athina Chatzigianni [2], Nikolaos Daratsianos [3] and Christoph Bourauel [1]

[1] Department of Oral Medical Technology, School of Dentistry, Faculty of Medicine, University of Bonn, 53111 Bonn, Germany; bourauel@uni-bonn.de
[2] Department of Orthodontics, School of Health Sciences, Faculty of Dentistry, Aristotle University of Thessaloniki, 54124 Thessaloniki, Greece; achatzigianni@dent.auth.gr
[3] Department of Orthodontics, School of Dentistry, Faculty of Medicine, University of Bonn, 53111 Bonn, Germany; nikolaos.daratsianos@uni-bonn.de
* Correspondence: chrystalla.s.kyprianou@gmail.com

Abstract: This study aimed to investigate the force values exerted from rectangular wires when combined with conventional labial and fully customized lingual appliances under predefined, idealized activation. Fully customized lingual brackets of two brands Incognito™ (3M Unitek, Monrovia, CA, USA) and WIN (DW Lingual Systems, Bad Essen, Germany) and labial brackets of another brand, discovery® MIM and discovery® smart systems (Dentaurum, Ispringen, Germany), were chosen. Stainless-steel and beta-titanium wires of 0.018″ × 0.025″ were examined. For Incognito™, 0.0182″ × 0.025″ beta-titanium wires were tested. Intrusion/extrusion and orovestibular movements were performed in a range of 0.2 mm, and the forces were recorded for each 0.1 mm of the movement. Mean values and standard deviations were calculated for all measurements, and ANOVA was performed for statistical analysis. Slight differences were observed between the forces generated from beta-titanium and stainless-steel wires. The same wire generated in some cases 5–53% higher forces with the lingual appliance due to the vertical orientation of the long walls during intrusion/extrusion and increased wire stiffness at the anterior region. Beta-titanium and stainless-steel 0.018″ × 0.025″ wires can generate similar force values during the final stages of the orthodontic therapy; thus, possibly only one of the two alloys could be used in each orthodontic wire sequence.

Keywords: orthodontics; lingual brackets; labial brackets; wires; forces; brackets; rectangular wires; stainless steel; beta titanium; TMA wires

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1. Introduction

Throughout the years, fixed appliances have evolved in an effort to ensure treatment efficacy, comfort and aesthetics, as well as reduced chair time and treatment duration. The superiority of modern treatment protocols is the topic of choice for many researchers, while others look into the possible side effects of fixed appliances, such as white spot lesions, enamel damage after debonding, root resorption or changes in the pulp metabolic activity during orthodontic therapy [1–4]. The introduction of new materials and the continuous improvement of existing ones highlight the necessity for further research.

Conventional metallic bracket systems are now competing with self-ligating or esthetic labial orthodontic appliances, while lingual bracket systems have been gaining ground in the preference of both patients and orthodontic professionals during the last two decades. Kurz et al. (1982) presented the first lingual bracket system, and Wiechman et al. (2002) pioneered the fully customized lingual appliances [5,6]. In the years ahead, various researchers investigated the treatment effects and mechanical properties of these appliances. Slot morphology and dimensions, as well as the slot play of the lingual appliances, were repeatedly studied [7,8]. The forces generated from the fully customized lingual appliances were previously investigated, however, the existing results result in controversy [9–11].

At the same time, several biomaterials are being used for the production of orthodontic wires of various diameters or cross sections, and miscellaneous wire sequence protocols have been proposed by different scientists [12]. Titanium molybdenum alloy (TMA) was introduced in the 1980s as an intermediate between nickel titanium (NiTi) and stainless-steel (SS) wires with an elastic modulus of 10.5 Msi (72.4 GPa) [13]. Morinaga et al. (1988) developed a method for the design of titanium alloys, which allowed reduction in the Young's modulus of these archwires [14]. Thermal treatments, which have the same effect on titanium wires, have been proposed by other scientists [15,16]. Kusy et al. (1983) calculated the ratios of the major properties, i.e., stiffness, strength and range of numerous alloys, including TMA and SS. According to these ratios, beta-titanium (β-Ti) shows lower strength, higher range and stiffness of one-third of SS [17]. The unique biomechanical properties of beta-titanium wires were investigated by several authors [18–22]. The TMA is still considered the most recent entrance in the production industry of conventional orthodontic wires, although new titanium alloys are proposed occasionally [23].

Regarding the comparison of different bracket/rectangular wire combinations, Daratsianos et al. (2016) and Tran et al. (2021) compared the torque capabilities of SS and β-Ti rectangular wires combined with labial and/or lingual appliances [8,24]. These investigators were driven by the fact that rectangular wires of the specific alloys are indicated as finishing wires when effective torque control is needed. In addition, particular archwires are ideal for segment stabilization and as a substitute of nickel titanium wires in cases of nickel allergies [25–27].

Based on the current literature, this study aimed to resolve the controversy over force values generated from fully customized lingual appliances and to compare the forces generated from stainless-steel and beta-titanium wires when combined with the selected bracket appliances. Furthermore, the authors intended to document the forces produced by rectangular wires of these alloys when combined with multiple bracket systems for the certain indications, which is something that has not been analyzed before. The experiment was performed under clearly predefined and idealized activation conditions. The null hypothesis was that there are no differences in the produced force levels of the tested bracket appliances and wire alloys.

2. Materials and Methods

2.1. Bracket Appliances and Wires

Four bracket appliances with 0.18 inch slots (Incognito™ lingual brackets (3M Unitek, Monrovia, CA, USA), WiN lingual brackets (DW Lingual Systems, Bad Essen, Germany), discovery® MIM and discovery® smart appliances (Dentaurum, Ispringen, Germany)) were combined with 0.018″ × 0.025″ β-Ti and 0.018″ × 0.025″ SS archwires. Specifically, Incognito™ offers 0.0182″ × 0.025″ beta-titanium wires. Preformed archwires (Rematitan® Special ideal arches/Remanium® ideal arches (Dentaurum, Ispringen, Germany)) were used for the labial appliances. For the fully individualized bracket systems, the licensed laboratories constructed customized wires (i.e., mushroom shaped with straight lateral segments) in order to fit a moderately crowded mandibular arch with rotated premolars [28].

The physical, mechanical and thermal properties of the selected archwires are shown in Table 1. All wire dimensions and slot lengths (according to ISO27020:2019) were registered by using a manual ratchet thimble micrometer (Mitutoyo America Corporation, Aurora, IL, USA) and a digimatic caliper (Mitutoyo Digimatic 500-120, Mitutoyo Deutschland GmbH, Neuss, North Rhine-Westphalia, Germany).

Table 1. Physical, mechanical and thermal properties of archwires. The wire dimensions in millimeters were calculated from manufacturers' values (0.018″ × 0.025″ and 0.0182″ × 0.025″). Young's moduli were calculated from Proffit [13].

		Dimensions (mm)	Young's Modulus (GPa)	Temperature Dependence
β-Ti	Incognito™	0.635 × 0.462	72	None
	WiN	0.635 × 0.457		
	Dentaurum	0.457 × 0.635		
SS	Incognito™	0.635 × 0.457	200	None
	WiN	0.635 × 0.457		
	Dentaurum	0.457 × 0.635		

2.2. Model

A full set of lingual brackets, archwires, transfer trays and setup models was received from each laboratory. For this investigation, only the setup models and the final customized wires were used. Prior to the customization of the Incognito™ appliances, the respective laboratory received a scanned copy of the WiN setup model in order to reproduce the aligned arch and manufacture archwires with a similar therapeutic goal.

Resin replicas (Technovit® 4004, Kulzer GmbH, Hanau, Germany) identical to the setup model received from the WiN laboratory were constructed. Forces were registered at three tooth positions: the canine (#33), the lateral incisor (#42) and the second premolar (#45). These teeth were removed from the casts in order to create space for the force/moment sensor. For both the labial and lingual appliances, a standard bonding procedure was followed. Wire splints were used to achieve slot leveling during the bonding procedure. The Transbond™ XT lightcure adhesive primer and paste (3M Unitek, Monrovia, CA, USA) and the Maximum Cure® sealants A and B (Reliance Orthodontics, Itasca, IL, USA) were used for the labial and lingual appliances, respectively.

Interbracket distances were measured with the use of an electronic caliper (Mitutoyo Digimatic 500–120, Mitutoyo Deutschland GmbH, Neuss, Germany) on the resin casts and on photos of the bonded setup models.

2.3. Apparatus

The experiment was performed in a temperature-controlled chamber (VEM 03/400, Heraeus Voetsch, Germany) of the orthodontic measurement and simulation system (OMSS) [29,30]. The chamber includes two force/moment sensors connected with three-dimensional positioning tables attached to stepping motors, which allow movement in the three planes of space. The apparatus was constructed based on the idea of a two-tooth model as described by Burstone and Koenig [31] and may be regarded as an electronic typodont, which continuously registers the force and moment values.

2.4. Activation Procedure

Each model was mounted in the OMSS chamber, and the sensor was adjusted in a position where the initial forces were neutralized. The selected wire piece was then ligated on the sensor and the neighboring teeth (Figure 1). The wires were ligated with Remanium® short, preformed ligatures (Dentaurum, Ispringen, Germany). For the specific study, each bracket/wire combination was actively moved (successive steps of 0.02 mm) on the x-axis and z-axis, while the 3D sensors detected the generated forces. In the specific configuration, displacement on the x-axis represented intrusion/extrusion, and displacement on the z-axis represented orovestibular movement. Forces were registered at 0.1 mm, 0.2 mm and then backwards, so both positive and negative activation movements were applied on all systems. Each time a new model was tested, the system was neutralized in order to guarantee that forces were eliminated at the initial position.

The activation process was performed separately at each tooth area, and each activation circle was repeated five times. The Incognito model was activated with new wires and new ligatures in each activation circle, while one set of wires was available for the WiN model; thus, the specific wire pieces were readjusted and religated for every repetition.

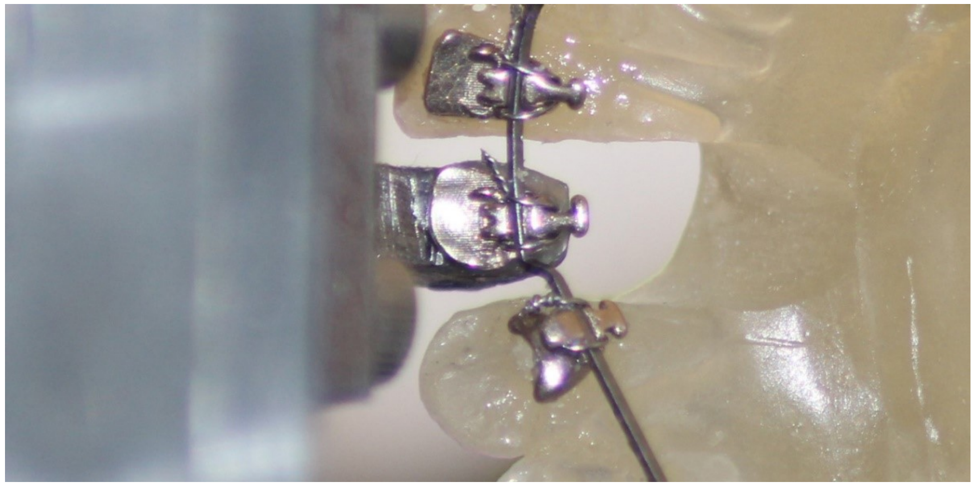

Figure 1. Resin cast bonded with the Incognito™ appliance and adjusted in the OMSS chamber.

2.5. Statistical Analysis

For each group of five repetitions, the mean value and the standard deviation were calculated. Subsequently, all mean values were tested for normal distribution using the Kolmogorov–Smirnov test. The one-way analysis of variance (ANOVA) was performed in order to identify differences between the various bracket-wire combinations for each direction and each 0.1 mm of the activation procedure. Student–Newman–Keuls tests were chosen as post-hoc tests mainly to avoid Type 1 error. Student's t-tests for equality of means were used for group comparisons between the two lingual and the two labial appliances, and the Levene's test of equality of variances was used to compare standard deviations. The statistical analysis was performed with the SPSS Statistics software version 9 (IBM, Armonk, New York, NY, USA).

3. Results

Table 2 shows the measured slot specifications for all bracket types and the interbracket distance. Table 3 presents the measured wire dimensions.

Table 2. Slot lengths (according to ISO27020:2019) and distance between the adjacent slots of all the appliances used in this study.

	Slot Length (mm)			
	Discovery® MIM	**Discovery® Smart**	**WiN**	**Incognito™**
Lower left 1st bicuspid (#34)	3.3	2.7	3.1	2.5
Lower left cuspid (#33)	2.9	2.7	2.5	2.3
Lower left lateral incisor (#32)	2.6	2.3	2.1	2.4
Lower right central incisor (#41)	2.6	2.3	2.1	2.4
Lower right lateral incisor (#42)	2.6	2.3	2.1	2.4
Lower right cuspid (#43)	3.0	2.7	2.5	2.4
Lower right 1st bicuspid (#44)	3.3	2.8	3.0	2.4
Lower right 2nd bicuspid (#45)	3.3	2.7	3.1	2.4
Lower right 1st molar (#46)	3.2	3.2	3.1	3.9

Table 2. *Cont.*

	Distance Between Adjacent Slots (mm)			
	Discovery® MIM	**Discovery® Smart**	**WiN**	**Incognito™**
#34–#33	4.5	4.9	3.0	3.4
#33–#32	4.2	4.9	2.8	3.0
#41–#42	3.1	3.7	3.0	2.9
#42–#43	4.6	5.3	2.2	2.2
#44–#45	3.6	4.0	3.3	4.1
#45–#46	5.7	6.6	4.7	4.4

Table 3. Measured dimensions of the selected wires. The nominal dimensions are 0.635 × 0.462 mm for beta-titanium wires received from Incognito™ and 0.635 × 0.457 mm for the rest of the wires.

	Wire Dimensions (mm)			
	Discovery® MIM	**Discovery® Smart**	**WiN**	**Incognito™**
SS1	0.440 × 0.624	0.442 × 0.626	0.632 × 0.457	0.622 × 0.451
SS2	0.441 × 0.624	0.440 × 0.622		0.623 × 0.450
SS3	0.441 × 0.622	0.444 × 0.620		0.623 × 0.453
SS4	0.445 × 0.623	0.443 × 0.621		0.620 × 0.452
SS5	0.445 × 0.622	0.440 × 0.622		0.620 × 0.452
β-Ti1	0.450 × 0.631	0.450 × 0.633	0.635 × 0.445	0.623 × 0.455
β-Ti2	0.443 × 0.628	0.450 × 0.628		0.623 × 0.455
β-Ti3	0.446 × 0.632	0.449 × 0.632		0.623 × 0.454
β-Ti4	0.449 × 0.630	0.450 × 0.632		0.624 × 0.455
β-Ti5	0.446 × 0.631	0.450 × 0.630		0.620 × 0.456

SS: stainless steel; β-Ti: beta titanium.

In general, the generated forces ranged between 0.4 N and 4.1 N for all the bracket types combined with the β-Ti wires and between 0.6 N and 4.7 N for all bracket types combined with SS wires.

3.1. Stainless-Steel Wires

Tables 4 and 5 present the force mean values observed during the activation procedure of the SS wire. According to ANOVA results, statistically significant differences between the four appliances were observed in all cases apart from the oral movement of the lateral incisor and the premolar (Table 5; (#42; 0.1 mm; Fz; $p = 0.699$); (#42; 0.2 mm; Fz; $p = 0.451$); (#45; 0.2 mm; Fz; $p = 0.388$)). In addition, lingual appliances generated higher forces at the premolar area during intrusion and extrusion movement ((Table 4; #45; Fx; 0.1 mm; $p = 0.000$ and 0.2 mm; $p = 0.000$), (Table 5; #45; Fx; 0.1 mm; $p = 0.000$ and 0.2 mm; $p = 0.022$)). At the canine and lateral incisor area, lingual appliances generated higher forces only during extrusion movement (Table 5; (#33; Fx; 0.1 mm; $p = 0.000$ and 0.2 mm; $p = 0.000$), (#42; Fx; 0.1 mm; $p = 0.000$ and 0.2 mm; $p = 0.000$)). Group comparisons showed statistically significant differences between appliances of the same type, i.e., between the two labial appliances and between the two lingual systems.

Table 4. Intrusion/extrusion and orovestibular force values generated during positive activation at a specific tooth (canine, lateral incisor and premolar) area using the four different bracket appliances combined with the stainless-steel wire at 0.1 mm and 0.2 mm.

Act+		Teeth under Examination											
		#33				#42				#45			
		0.1 mm		0.2 mm		0.1 mm		0.2 mm		0.1 mm		0.2 mm	
Brackets	Wires	Fx (N)	Fz (N)	Fx (N)	Fz (N)	Fx (N)	Fz (N)	Fx (N)	Fz (N)	Fx (N)	Fz (N)	Fx (N)	Fz (N)
D	SS	-1.3^{a}	-1.1^{r}	-2.7^{c}	-1.8^{u}	-1.7^{f}	-1.5^{x}	$-3.4^{i,k}$	-2.2^{j}	$-1.9^{m,n}$	-0.7^{φ}	-3.3^{p}	-1.5^{ω}
Ds	SS	-2.0^{b}	-1.0^{r}	-3.5^{d}	-1.6^{u}	-1.3^{g}	-1.0^{y}	-3.0^{k}	-1.9^{l}	-1.5^{m}	-1.3^{ψ}	-2.7^{p}	-2.2^{β}
W	SS	-2.5^{b}	-0.6^{s}	$-3.0^{c,d}$	-1.0^{v}	-2.1^{f}	-0.9^{y}	-2.8^{k}	-1.4^{θ}	-2.9^{n}	-1.1^{ψ}	-4.7^{q}	$-1.7^{\omega,\beta}$
I	SS	-2.5^{b}	-1.7^{t}	-4.2^{e}	-2.8^{w}	-2.6^{h}	-1.7^{z}	-3.9^{i}	-2.8^{λ}	-2.3^{o}	-1.2^{ψ}	-4.7^{q}	$-1.9^{\omega,\beta}$
p value for ANOVA		0.000	0.000	0.000	0.000	0.000	0.000	0.004	0.000	0.000	0.001	0.000	0.013

Act+: Positive activation; Fx: Forces generated during the intrusion; Fz: Forces generated during the vestibular movement (see Figure I). D: discovery® MIM; Ds: discovery® smart; W: WiN; I: Incognito™; N: Newton. $^{a–z}$: Values marked with the same letter do not differ according to Student–Newman–Keuls post-hoc tests.

Table 5. Intrusion/extrusion and orovestibular force values generated during negative activation at a specific tooth (canine, lateral incisor and premolar) area using the four different bracket appliances combined with the stainless-steel wire at 0.1 mm and 0.2 mm.

Act-		Teeth under Examination											
		#33				#42				#45			
		0.1 mm		0.2 mm		0.1 mm		0.2 mm		0.1 mm		0.2 mm	
Brackets	Wires	Fx (N)	Fz (N)	Fx (N)	Fz (N)	Fx (N)	Fz (N)	Fx (N)	Fz (N)	Fx (N)	Fz (N)	Fx (N)	Fz (N)
D	SS	1.7^{a}	1.6^{q}	2.3^{c}	2.5^{t}	2.4^{f}	2.0^{w}	3.2^{i}	2.8^{x}	1.8^{l}	1.3^{y}	2.5^{o}	2.1^{θ}
Ds	SS	1.7^{a}	1.3^{q}	2.3^{c}	1.9^{u}	1.4^{g}	2.2^{w}	2.2^{j}	3.0^{x}	1.8^{l}	1.3^{y}	2.4^{o}	2.3^{θ}
W	SS	3.1^{b}	3.1^{r}	3.9^{d}	3.4^{v}	3.0^{h}	2.2^{w}	4.1^{k}	2.8^{x}	3.0^{m}	1.8^{z}	3.6^{p}	2.2^{θ}
I	SS	3.0^{b}	2.0^{s}	4.6^{e}	2.7^{t}	2.8^{h}	2.4^{w}	3.9^{k}	3.0^{x}	2.4^{n}	$1.5^{y,z}$	3.3^{p}	2.4^{θ}
p value for ANOVA		0.000	0.000	0.000	0.000	0.000	0.699	0.000	0.451	0.000	0.000	0.022	0.388

Act-: Negative activation; Fx: Forces generated during the extrusion; Fz: Forces generated during the oral movement. D: discovery® MIM; Ds: discovery® smart; W: WiN; I: Incognito™; N: Newton. $^{a–z}$: Values marked with the same letter do not differ according to Student–Newman–Keuls post-hoc tests.

3.2. Beta-Titanium Wires

Tables 6 and 7 show the mean values recorded during the activation of the β-Ti wire. In agreement with the activation of the SS wire, ANOVA proved that the forces generated from the lingual systems were significantly higher than those generated by the labial appliances during the intrusion and the extrusion of the premolar ((Table 6; #45; Fx; 0.1 mm; $p = 0.000$ and 0.2 mm; $p = 0.000$), (Table 7; #45; Fx; 0.1 mm; $p = 0.000$ and 0.2 mm; $p = 0.000$)). The lateral incisor presented the same pattern ((Table 6; #42; Fx; 0.1 mm; $p = 0.000$), (Table 7; #42; Fx; 0.1 mm; $p = 0.000$ and 0.2 mm; $p = 0.000$)). At the canine area, forces produced by labial appliances were lower during extrusion (Table 7; #33; Fx; 0.1 mm; $p = 0.000$ and 0.2 mm; $p = 0.000$) and orovestibular activation ((Table 6; #33; Fz; 0.1 mm; $p = 0.000$ and 0.2 mm; $p = 0.000$), (Table 7; #33; Fz; 0.1 mm; $p = 0.000$ and 0.2 mm; $p = 0.000$)). During the orovestibular movement of the lateral incisor, lingual and labial appliances generated approximately the same force values ((Table 6; #42; Fz; 0.1 mm; $p = 0.264$), (Table 7; #42; Fz; 0.1 mm; $p = 0.054$)). Student's t-tests showed several differences between the brackets of the same type.

Table 6. Intrusion/extrusion and orovestibular force values generated during positive activation at a specific tooth (canine, lateral incisor and premolar) area using the four different bracket appliances combined with the beta-titanium wire at 0.1 mm and 0.2 mm.

Act+		**Teeth under Examination**											
		#33				**#42**				**#45**			
		0.1 mm		**0.2 mm**		**0.1 mm**		**0.2 mm**		**0.1 mm**		**0.2 mm**	
Brackets	**Wires**	**Fx (N)**	**Fz (N)**	**Fx (N)**	**Fz (N)**	**Fx (N)**	**Fz (N)**	**Fx (N)**	**Fz (N)**	**Fx (N)**	**Fz (N)**	**Fx (N)**	**Fz (N)**
D	β-Ti	−1.1 [b]	−1.0 [s]	−2.1 [d]	−1.5 [u]	−1.4 [f]	−1.2 [x]	−2.7 [i]	−2.0 [y]	−1.4 [k]	−1.0 [θ]	−2.6 [o]	−1.5 [ψ]
Ds	β-Ti	−1.8 [a]	−0.9 [s]	−3.4 [e]	−1.5 [u]	−1.1 [f]	−1.2 [x]	−2.6 [i]	−1.9 [y]	−1.2 [l]	−1.4 [λ]	−2.3 [p]	−2.1 [ω]
W	β-Ti	−1.9 [a]	−1.7 [t]	−2.3 [d]	−2.8 [v]	−2.2 [g]	−1.1 [x]	−3.0 [i]	−1.8 [y]	−2.1 [m]	−0.4 [φ]	−4.0 [q]	−0.7 [γ]
I	β-Ti	−1.4 [c]	−1.4 [t]	−2.5 [d]	−2.2 [w]	−2.6 [h]	−1.4 [x]	−4.1 [j]	−2.5 [z]	−1.9 [n]	−0.8 [θ]	−3.8 [r]	−1.4 [ψ]
p value for ANOVA		0.000	0.000	0.000	0.000	0.000	0.264	0.001	0.000	0.000	0.001	0.000	0.013

Act+: Positive activation; Fx: Forces generated during the intrusion; Fz: Forces generated during the vestibular movement. D: discovery® MIM; Ds: discovery® smart; W: WiN; I: Incognito™; N: Newton. [a–z]: Values marked with the same letter do not differ according to Student–Newman–Keuls post -hoc tests.

Table 7. Intrusion/extrusion and orovestibular force values generated during negative activation at a specific tooth (canine, lateral incisor and premolar) area using the four different bracket appliances combined with the beta-titanium wire at 0.1 mm and 0.2 mm.

Act-		**Teeth under Examination**											
		#33				**#42**				**#45**			
		0.1 mm		**0.2 mm**		**0.1 mm**		**0.2 mm**		**0.1 mm**		**0.2 mm**	
Brackets	**Wires**	**Fx (N)**	**Fz (N)**	**Fx (N)**	**Fz (N)**	**Fx (N)**	**Fz (N)**	**Fx (N)**	**Fz (N)**	**Fx (N)**	**Fz (N)**	**Fx (N)**	**Fz (N)**
D	β-Ti	1.5 [a]	1.4 [q]	2.1 [c]	2.2 [t]	1.9 [e]	1.8 [w]	2.7 [h]	2.5 [y,z]	1.5 [k]	1.5 [θ]	2.1 [n]	2.4 [λ]
Ds	β-Ti	1.6 [a]	1.3 [q]	2.2 [c]	1.9 [t]	1.4 [f]	1.9 [w,x]	2.2 [i]	2.7 [y]	1.7 [k]	1.9 [θ,ω]	2.3 [n]	2.8 [λ]
W	β-Ti	2.6 [b]	2.6 [r]	3.4 [d]	3.5 [u]	2.6 [g]	1.6 [w,x]	3.4 [j]	2.9 [z]	2.7 [l]	2.1 [ω]	3.2 [o]	2.5 [λ]
I	β-Ti	2.5 [b]	2.1 [s]	3.1 [d]	2.7 [v]	2.5 [g]	2.2 [x]	3.3 [j]	2.2 [y]	2.1 [m]	1.6 [θ]	2.8 [p]	2.0 [ψ]
p value for ANOVA		0.000	0.000	0.000	0.000	0.000	0.054	0.000	0.006	0.000	0.004	0.000	0.002

Act-: Negative activation; Fx: Forces generated during the extrusion; Fz: Forces generated during the oral movement. D: discovery® MIM; Ds: discovery® smart; W: WiN; I: Incognito™; N: Newton. [a–z]: Values marked with the same letter do not differ according to Student–Newman–Keuls post-hoc tests.

In most cases, the forces generated by the bracket/β-Ti combination were slightly lower than those generated from the combination of the SS wire with the same bracket appliance (Figure 2). On the contrary, in 20 out of 96 cases, the β-Ti wires generated slightly higher forces as shown in Figure 3. All these cases represented orovestibular movements.

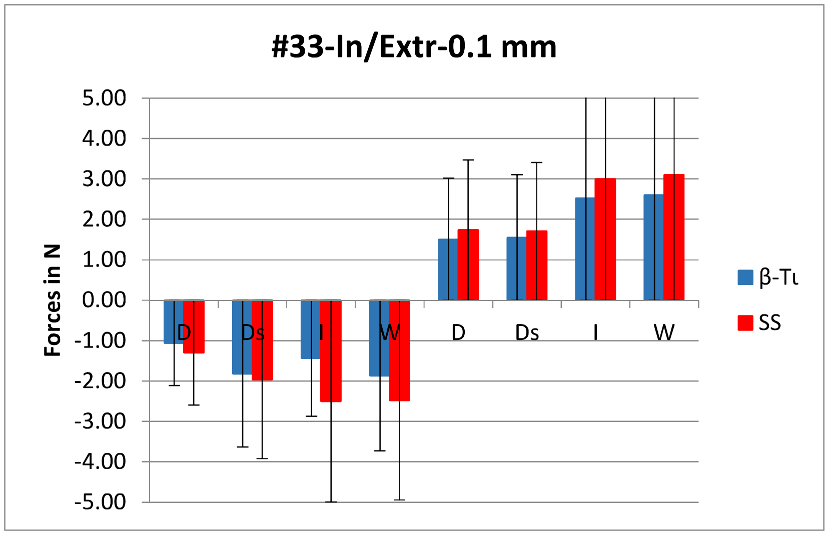

Figure 2. Graphic representation of the forces generated at 0.1 mm of the intrusion and extrusion of the canine (#33). SS: stainless steel; β-Ti: beta titanium; D: discovery® MIM; Ds: discovery® smart; W: WiN; I: Incognito™; N: Newton.

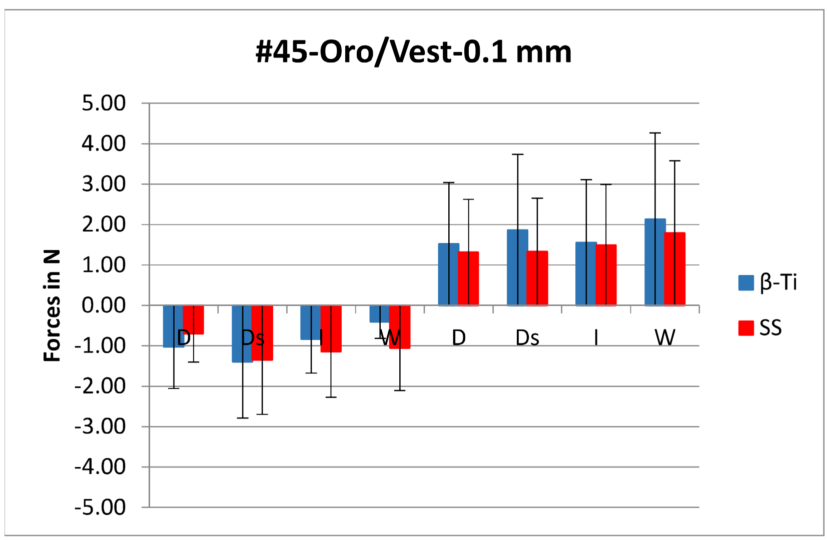

Figure 3. Graphic representation of the forces generated at the 0.1mm of the orovestibular movement of the premolar (#45). SS: stainless steel; β-Ti: beta titanium; D: discovery® MIM; Ds: discovery® smart; W: WiN, I: Incognito™; N: Newton.

4. Discussion

The force systems of labial and fully customized lingual bracket systems at teeth of different types, inclinations and positions were investigated. Due to the rigid nature of the selected wire types, it was impossible to experiment on a malocclusion model; thus, copies of the setup model were used to represent the final stage of the alignment.

According to the results of this study, the null hypothesis must be rejected since differences were observed between the dissimilar bracket appliances and the different wire alloys.

The selected bracket appliances had a 0.018″ slot size with horizontal "edgewise" orientation of the long slot walls apart from the lingual brackets, which had vertical "ribbonwise" orientation of the long slot walls, whereas the incisor and canine lingual brackets also had a vertical slot opening. The vertical orientation of the inserted wire in the lingual slots explains the higher force values generated from the fully customized lingual appliances during the intrusion and extrusion in comparison with the values generated from the labial appliances during activation on the same axis. In addition, forces generated from the lingual systems during the intrusion/extrusion were higher from those produced during the orovestibular activation of the wires due to the abovementioned reason. The use of lingual appliances can also result in higher force values because of the reduced free wire length and increased wire stiffness at the anterior region, which results from the morphology of the lingual bracket systems [10,11,32,33]. An example is the higher forces generated at the canine area during the orovestibular activation. For the lingual appliances, the 0.018″ × 0.025″ β-Ti archwires are indicated as finishing wires in cases where high torque expression is needed, while the SS wires are indicated for stabilization and anchorage during orthodontic or orthognathic therapy and for anchorage in combination with the Herbst device. Taking into consideration the specific indications of the wires mentioned above, the higher force levels could be beneficial in clinical practice and, especially, in cases where the orthodontist seeks methods to increase anchorage. The distances between the central incisor (#41) and the lateral incisor (#42) for the Discovery® MIM appliance and the lingual appliances were the same. The lingual interbracket distances between the lateral incisor (#42) and the canine (#43) were half of the labial interbracket distances. Due to the larger slot widths, the Win interbracket distance between the first (#44) and second premolar (#45) was smaller, while the Incognito™ brackets had the same interbracket distance as the Discovery® smart appliance. The lingual interbracket distances between the second premolar (#45) and the first molar (#46) were smaller in comparison with labial interbracket distances. For the lingual bracket systems, the "ribbonwise" wire orientation results in smaller orovestibular forces in comparison with the labial appliances. The interbracket distances, in combination with the wire orientation in each case, resulted in similar orovestibular forces for the labial and lingual appliances at the lateral incisor and premolar areas.

The effects of orthodontic force on dental pulp and the apical foramen are of great importance. Histological and metabolic pulp changes have been observed in patients under orthodontic treatment [2,34]. Moreover, apical root resorption (ARR) has been associated with intrusion forces [35,36]. Risk factors, such us the force magnitude, the age of the patient, the tooth type, the treatment duration and the range of movement, should be taken into consideration [36–38]. Variances observed between activations on the same axis (i.e., between intrusion and extrusion or oral and vestibular activation) have multifactorial etiology. Firstly, the selected wires faced resistance from the slot walls or the ligature depending on the activation direction. Since the ligatures are far more elastic than the slot walls, a force, which results against the ligatures, can be lower. Secondly, slight differences could result from inconsistent ligation pressure and unalike wire adjustment.

Forces varied between the five activation repetitions with the same wire material. This observation confirms previous investigations, which showed that the use of different pieces of wire of the same alloy and dimensions could result in diverse force values [39,40]. Furthermore, the consecutive wire insertions and sensor adjustments could result in different contact status between the selected wires and bracket appliances, which is a typical measurement error.

Several statistically significant variances that were registered between the four appliances had no clinical significance. Differences of a few micrometers might be statistically significant but do not affect the overall treatment outcome.

Several authors reported that β-Ti wires have lower elastic modulus and, thus, generate lower forces at the same amount of deflection in comparison with the SS wires [13,20,41]. In this study, the differences between the two wire alloys were small. A possible explanation is the higher static and kinetic frictional resistance of the β-Ti alloy in comparison with the stainless-steel wires [42–45]. Previous investigations proved the adherence between the β-Ti alloy and the stainless-steel bracket surfaces, which result in higher friction forces [46].

The beta-titanium wires also present higher surface roughness than the stainless-steel ones; however, the correlation between wire surface roughness and friction is still a controversial subject [44,47,48]. The width and height of each wire piece were registered, and the dimensions of the β-Ti wires were found slightly larger than those of the SS wires. Furthermore, due to the larger dimensions of the beta-titanium wires, the slot play was smaller, and the consequent friction forces increased. These factors could have affected the resulting force values.

4.1. Sources of Error

Errors relative to the obtained values could arise from various aspects of the experimental procedure, such as model scanning and duplication, positioning of the brackets, the wires and the sensor and sensor accuracy and statistical error of repetition. Model scanning proved to be a reliable method for digitizing the classic stone casts [49,50]. Stone cast duplication is very common in dentistry, and the precision of silicone has been analyzed before [51–53]. Moreover, measurements on stone models with the use of calipers proved to be comparable with the use of three dimensional software [54]. The positioning of the brackets, the bonding procedure using transfer keys, the wire adjustments and ligation were performed by the same examiner following a standardized protocol. It is difficult to quantify this error source, which has an effect on the positioning accuracy of brackets and wires in the measurement model. However, as all the steps have been performed by one examiner using transfer keys and identical material was used, we assume that the effect on the overall error might be neglected compared to the other error sources.

The maximum sensor error in linearity is 0.3% and 1.8% due to cross-talk, resulting in an overall sensor error of 0.02 N for forces and 0.5 Nmm for torques [30], which is below 1% of the measured maximum forces. The positioning resolution of the OMSS is 1 µm, which again is less than 1 % of the maximum activation and could have similar effects on the force errors [30].

Finally, a possible additional source of error in the force measurements might be the wire/slot play of the wire inserted into the slot of the measurement bracket. Although the measurement bracket is adjusted to deliver force and torque readings of 0.0 N (Nmm) any time prior to start of the activation measurement, we cannot exclude the possibility that the wire slot play might have a varying influence on the individual force/torque measurements. Taking the nominal slot height of 0.457 mm (0.018″) and wire dimensions from Table 3, it becomes obvious that the wire/slot play might reach values of up to 0.037 mm for Incognito and 0.025 mm for the Win appliances. For the standard appliances, maximum play reaches 0.017 mm. Thus, wire/slot play might reach 10% or even more of the maximum measured deflection and obviously seems to have the highest influence on measured force error of these activation measurements.

In order to reduce random error, the force measurements were repeated five times in each direction, and only the mean values were compared. By calculating the overall error from the above cited error sources using Gaussian's law of error propagation, we can estimate a maximum systematic and measurement error of 15% within which the wire/slot play has decisive influence. This is consistent with clinical experience that wire/slot play has decisive influences on tooth positions in the final adjustment phase.

4.2. Limitations

The limitations of this experimental investigation are as follows: (1) experimentation in an idealized environment (simulation device) without periodontal ligament, mobility of the adjacent teeth, occlusion, muscle forces and saliva; and (2) the use of stainless-steel ligatures. Stainless-steel ligatures result in reduced friction forces compared to elastic ligatures [55]. Previous investigations presented controversial results regarding the influence of saliva on friction and the resultant orthodontic forces [56,57]. In addition, the fully customized lingual appliances are always customized on a VTO setup model, while the labial appliances were not. The force values described above might differ from those generated in clinical practice because of these limitations; thus, the obtained values are used only as a standard of comparison between the dissimilar bracket systems and wire alloys.

5. Conclusions

The differences between the force values generated from the β-Ti and the SS 0.018″ × 0.025″ wires were small. Within the limits of this study, we could assume that possibly only one of the two archwire alloys could be used as a part of a wire sequence during the orthodontic therapy; however, further investigation is needed. Specifically, the moment values generated from the particular bracket/wire combinations should also be investigated in order to draw conclusions. Higher forces (5–53%) were generated in some cases from the lingual appliances in comparison with the forces produced from the labial appliances when tested with the same wire. These forces could be beneficial in clinical practice in cases where increased anchorage is needed.

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References

1. D'Amario, M.; Bernardi, S.; Di Lauro, D.; Marzo, G.; Macchiarelli, G.; Capogreco, M. Debonding and Clean-Up in Orthodontics: Evaluation of Different Techniques and Micro-Morphological Aspects of the Enamel Surface. *Dent. J.* **2020**, *17*, 58. [CrossRef]
2. Perinetti, G.; Varvara, G.; Salini, L.; Tetè, S. Alkaline phosphatase activity in dental pulp of orthodontically treated teeth. *Am. J. Orthod. Dentofac. Orthop.* **2005**, *128*, 492–496. [CrossRef]
3. Knösel, M.; Klang, E.; Helms, H.J.; Wiechmann, D. Occurrence and severity of enamel decalcification adjacent to bracket bases and sub-bracket lesions during orthodontic treatment with two different lingual appliances. *Eur. J. Orthod.* **2016**, *38*, 485–492. [CrossRef]
4. Maués, C.P.; do Nascimento, R.R.; Vilella Ode, V. Severe root resorption resulting from orthodontic treatment: Prevalence and risk factors. *Dent. Press J. Orthod.* **2015**, *20*, 52–58. [CrossRef] [PubMed]
5. Kurz, C.; Swartz, M.L.; Andreiko, C. Lingual orthodontics: A status report. Part 2: Research and development. *J. Clin. Orthod.* **1982**, *16*, 735–740. [PubMed]
6. Wiechmann, D. A new bracket system for lingual orthodontic treatment. Part 1: Theoretical background and development. *J. Orofac. Orthop.* **2002**, *63*, 234–245. [CrossRef]
7. Choi, S.; Kim, J.H.; Kim, N.J.; Lee, S.H.; Kim, H.; Kim, K.A.; Park, K.H.; Park, Y.G. Morphological investigation of various orthodontic lingual bracket slots using scanning electron microscopy and atomic force microscopy. *Microsc. Res. Tech.* **2016**, *79*, 1193–1199. [CrossRef]
8. Daratsianos, N.; Bourauel, C.; Fimmers, R.; Jäger, A.; Schwestka-Polly, R. In vitro biomechanical analysis of torque capabilities of various 0.018″ lingual bracket-wire systems: Total torque play and slot size. *Eur. J. Orthod.* **2016**, *38*, 459–469. [CrossRef] [PubMed]
9. Fuck, L.M.; Wiechmann, D.; Drescher, D. Comparison of the initial orthodontic force systems produced by a new lingual bracket system and a straight-wire appliance. *J. Orofac. Orthop.* **2005**, *66*, 363–376. [CrossRef]
10. Sifakakis, I.; Pandis, N.; Makou, M.; Katsaros, C.; Eliades, T.; Bourauel, C. A comparative assessment of forces and moments generated by lingual and conventional brackets. *Eur. J. Orthod.* **2013**, *35*, 82–86. [CrossRef]
11. Alobeid, A.; El-Bialy, T.; Khawatmi, S.; Dirk, C.; Jäger, A.; Bourauel, C. Comparison of the force levels among labial and lingual self-ligating and conventional brackets in simulated misaligned teeth. *Eur. J. Orthod.* **2017**, *39*, 419–425. [CrossRef] [PubMed]

12. Papageorgiou, S.N.; Konstantinidis, I.; Papadopoulou, K.; Jäger, A.; Bourauel, C. A systematic review and meta-analysis of experimental clinical evidence on initial aligning archwires and archwire sequences. *Orthod. Craniofac. Res.* **2014**, *17*, 197–215. [CrossRef]
13. Proffit, W.R.; Fields Junior, H.W.; Sarver, D.M. *Contemporary Orthodontics*, 4th ed.; Mosby: St. Louis, MO, USA, 2007; pp. 362; 365–366.
14. Morinaga, M.; Yukawa, N.; Maya, T.; Sone, K.; Adachi, H. Theoretical design of titanium alloys. In Proceedings of the 6th World Conference on Titanium, Cannes, France, 6–9 June 1988; pp. 1601–1606.
15. Kim, H.Y.; Kim, J.I.; Inamura, T.; Hosoda, H.; Miyazaki, S. Effect of thermo-mechanical treatment on mechanical properties and shape memory behavior of Ti–(26–28)at.% Nb alloys. *Mater. Sci. Eng. A* **2006**, *438*, 839–843. [CrossRef]
16. Sun, F.; Nowak, S.; Gloriant, T.; Laheurte, P.; Eberhardt, A.; Prima, F. Influence of a short thermal treatment on the superelastic properties of a titanium-based alloy. *Scr. Mater.* **2010**, *63*, 1053–1056. [CrossRef]
17. Kusy, R.P. On the use of nomograms to determine the elastic property ratios of orthodontic archwires. *Am. J. Orthod.* **1983**, *83*, 374–381. [CrossRef]
18. Verstrynge, A.; Van Humbeeck, J.; Willems, G. In-vitro evaluation of the material characteristics of stainless steel and beta-titanium orthodontic wires. *Am. J. Orthod. Dentofac. Orthop.* **2006**, *130*, 460–470. [CrossRef]
19. Lombardo, L.; Carlucci, A.; Palone, M.; Mollica, F.; Siciliani, G. Stiffness comparison of mushroom and straight SS and TMA lingual archwires. *Prog. Orthod.* **2016**, *17*, 27. [CrossRef]
20. Johnson, E. Relative stiffness of beta titanium archwires. *Angle Orthod.* **2003**, *73*, 259–269. [CrossRef]
21. Alsabti, N.; Bourauel, C.; Talic, N. Comparison of force loss during sliding of low friction and conventional TMA orthodontic archwires: An in vitro study. *J. Orofac. Orthop.* **2021**, *82*, 218–225. [CrossRef]
22. Whitley, J.Q.; Kusy, R.P. Resistance to sliding of titanium brackets tested against stainless steel and beta-titanium archwires with second-order angulation in the dry and wet states. *Am. J. Orthod. Dentofac. Orthop.* **2007**, *131*, 400–411. [CrossRef]
23. Seixas, M.R.; Konatu, R.T.; Rangel, A.L.R.; Hilsdorf, G.O.R.; Pereirajr, A.; Alves Claro, A.P.R. Study of a new titanium alloy for orthodontic applications. *Materials* **2013**, *29* (Suppl. 1), e1–e96. [CrossRef]
24. Tran, B.; Nobes, D.S.; Major, P.W.; Carey, J.P.; Romanyk, D.L. Research paper: The three-dimensional mechanical response of orthodontic archwires and brackets in vitro during simulated orthodontic torque. *J. Mech. Behav. Biomed. Mater.* **2021**, *114*, 104196. [CrossRef]
25. Mandall, N.; Lowe, C.; Worthington, H.; Sandler, J.; Derwent, S.; Abdi-Oskouei, M.; Ward, S. Which orthodontic archwire sequence? A randomized clinical trial. *Eur. J. Orthod.* **2006**, *28*, 561–566. [CrossRef]
26. Kerosuo, H.; Kullaa, A.; Kerosuo, E.; Kanerva, L.; Hensten-Pettersen, A. Nickel allergy in adolescents in relation to orthodontic treatment and piercing of ears. *Am. J. Orthod. Dentofac. Orthop.* **1996**, *109*, 148–154. [CrossRef]
27. Mortz, C.G.; Lauritsen, J.M.; Bindslev-Jensen, C.; Andersen, K.E. Nickel sensitization in adolescents and association with ear piercing, use of dental braces and hand eczema. The Odense Adolescence Cohort Study on Atopic Diseases and Dermatitis (TOACS). *Acta Derm. Venereol.* **2002**, *82*, 359–364. [CrossRef] [PubMed]
28. Kyprianou, C.; Chatzigianni, A.; Daratsianos, N.; Bourauel, C. Comparative investigation of fully customized lingual bracket systems and conventional labial appliances: Analysis of forces/moments and final tooth positions. *Am. J. Orthod. Dentofac. Orthop.* **2021**. Accepted for publication.
29. Drescher, D.; Bourauel, C.; Thier, M. Application of the orthodontic measurement and simulation system (OMSS) in orthodontics. *Eur. J. Orthod.* **1991**, *13*, 169–178. [CrossRef] [PubMed]
30. Bourauel, C.; Drescher, D.; Thier, M. An experimental apparatus for the simulation of three-dimensional movements in orthodontics. *J. Biomed. Eng.* **1992**, *14*, 371–378. [CrossRef]
31. Burstone, C.J.; Koenig, H.A. Force systems from an ideal arch. *Am. J. Orthod. Dentofac. Orthop.* **1974**, *65*, 270–289. [CrossRef]
32. Creekmore, T.D. The importance of interbracket width in orthodontic tooth movement. *J. Clin. Orthod.* **1976**, *10*, 530–534.
33. Moran, K.I. Relative wire stiffness due to lingual versus labial interbracket distance. *Am. J. Orthod. Dentofac. Orthop.* **1987**, *92*, 24–32. [CrossRef]
34. Abtahi, M.; Eslami, N.; Abadi, R.Z.; Rezaei, S.P. The effect of intrusive orthodontic force on dental pulp of adults versus adolescents. *Dent. Res. J.* **2016**, *13*, 367–372. [CrossRef]
35. Wang, H.; Li, T.; Wang, X.; Guan, Y.; Jiang, Y.; Chen, S.; Zou, S.; Duan, P. Mechanisms of sphingosine-1-phosphate (S1P) signaling on excessive stress-induced root resorption during orthodontic molar intrusion. *Clin. Oral Investig.* **2021**. Epub ahead of print. [CrossRef]
36. Akl, H.E.; El-Beialy, A.R.; El-Ghafour, M.A.; Abouelezz, A.M.; El Sharaby, F.A. Root resorption associated with maxillary buccal segment intrusion using variable force magnitudes: A randomized clinical trial. *Angle Orthod.* **2021**. Epub ahead of print. [CrossRef]
37. Bayir, F.; Bolat Gumus, E. External apical root resorption after orthodontic treatment: Incidence, severity and risk factors. *J. Dent. Res. Dent. Clin. Dent. Prospect.* **2021**, *15*, 100–105. [CrossRef] [PubMed]
38. Pinheiro, L.H.M.; Guimarães, L.S.; Antunes, L.S.; Küchler, E.C.; Kirschneck, C.; Antunes, L.A.A. Genetic variation involved in the risk to external apical root resorption in orthodontic patients: A systematic review. *Clin. Oral Investig.* **2021**, *25*, 5613–5627. [CrossRef] [PubMed]

39. Pompei-Reynolds, R.C.; Kanavakis, G. Interslot variations of transition temperature range and force delivery in copper-nickel-titanium orthodontic wires. *Am. J. Orthod. Dentofac. Orthop.* **2014**, *146*, 215–226. [CrossRef] [PubMed]
40. 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*, 285–296. [CrossRef]
41. Kusy, R.P. A review of contemporary archwires: Their properties and characteristics. *Angle Orthod.* **1997**, *67*, 197–207. [CrossRef] [PubMed]
42. Cacciafesta, V.; Sfondrini, M.F.; Ricciardi, A.; Scribante, A.; Klersy, C.; Auricchio, F. Evaluation of friction of stainless steel and esthetic self-ligating brackets in various bracket-archwire combinations. *Am. J. Orthod. Dentofac. Orthop.* **2003**, *124*, 395–402. [CrossRef]
43. Cash, A.; Curtis, R.; Garrigia-Majo, D.; McDonald, F. A comparative study of the static and kinetic frictional resistance of titanium molybdenum alloy archwires in stainless steel brackets. *Eur. J. Orthod.* **2004**, *26*, 105–111. [CrossRef]
44. Doshi, U.H.; Bhad-Patil, W.A. Static frictional force and surface roughness of various bracket and wire combinations. *Am. J. Orthod. Dentofac. Orthop.* **2011**, *139*, 74–79. [CrossRef] [PubMed]
45. Drescher, D.; Bourauel, C.; Schumacher, H.A. Frictional forces between bracket and arch wire. *Am. J. Orthod. Dentofac. Orthop.* **1989**, *96*, 397–404. [CrossRef]
46. Kusy, R.P.; Whitley, J.Q. Coefficients of friction for arch wires in stainless steel and polycrystalline alumina bracket slots. I. The dry state. *Am. J. Orthod. Dentofac. Orthop.* **1990**, *98*, 300–312. [CrossRef]
47. Fidalgo, T.K.; Pithon, M.M.; Maciel, J.V.; Bolognese, A.M. Friction between different wire bracket combinations in artificial saliva—An in vitro evaluation. *J. Appl. Oral Sci.* **2011**, *19*, 57–62. [CrossRef]
48. Nishio, C.; da Motta, A.F.; Elias, C.N.; Mucha, J.N. In vitro evaluation of frictional forces between archwires and ceramic brackets. *Am. J. Orthod. Dentofac. Orthop.* **2004**, *125*, 56–64. [CrossRef]
49. Amuk, N.G.; Karsli, E.; Kurt, G. Comparison of dental measurements between conventional plaster models, digital models obtained by impression scanning and plaster model scanning. *Int. Orthod.* **2019**, *17*, 151–158. [CrossRef]
50. Kirschneck, C.; Kamuf, B.; Putsch, C.; Chhatwani, S.; Bizhang, M.; Danesh, G. Conformity, reliability and validity of digital dental models created by clinical intraoral scanning and extraoral plaster model digitization workflows. *Comput. Biol. Med.* **2018**, *100*, 114–122. [CrossRef]
51. Peutzfeldt, A.; Asmussen, E. Accuracy of alginate and elastomeric impression materials. *Scand. J. Dent. Res.* **1989**, *97*, 375–379. [CrossRef] [PubMed]
52. Vitti, R.P.; da Silva, M.A.; Consani, R.L.; Sinhoreti, M.A. Dimensional accuracy of stone casts made from silicone-based impression materials and three impression techniques. *Braz. Dent. J.* **2013**, *24*, 498–502. [CrossRef] [PubMed]
53. Cho, S.H.; Schaefer, O.; Thompson, G.A.; Guentsch, A. Comparison of accuracy and reproducibility of casts made by digital and conventional methods. *J. Prosthet. Dent.* **2015**, *113*, 310–315. [CrossRef] [PubMed]
54. Wan Hassan, W.N.; Othman, S.A.; Chan, C.S.; Ahmad, R.; Ali, S.N.; Abd Rohim, A. Assessing agreement in measurements of orthodontic study models: Digital caliper on plaster models vs. 3-dimensional software on models scanned by structured-light scanner. *Am. J. Orthod. Dentofac. Orthop.* **2016**, *150*, 886–895. [CrossRef]
55. Vinay, K.; Venkatesh, M.J.; Nayak, R.S.; Pasha, A.; Rajesh, M.; Kumar, P. A comparative study to evaluate the effects of ligation methods on friction in sliding mechanics using 0.022" slot brackets in dry state: An In-vitro study. *J. Int. Oral Health* **2014**, *6*, 76–83. [PubMed]
56. Thorstenson, G.A.; Kusy, R.P. 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. Orofac. Orthop.* **2001**, *120*, 361–370. [CrossRef] [PubMed]
57. Phukaoluan, A.; Khantachawana, A.; Kaewtatip, P.; Dechkunakorn, S.; Anuwongnukroh, N.; Santiwong, P.; Kajornchaiyakul, J. Comparison of friction forces between stainless orthodontic steel brackets and TiNi wires in wet and dry conditions. *Int. Orthod.* **2017**, *15*, 13–24. [CrossRef]

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