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CLINICAL APPLICATIONS OF BIOMATERIALS

Original Research

An in vitro assessment of the influences of different wire materials and bracket systems when correcting dental crowding

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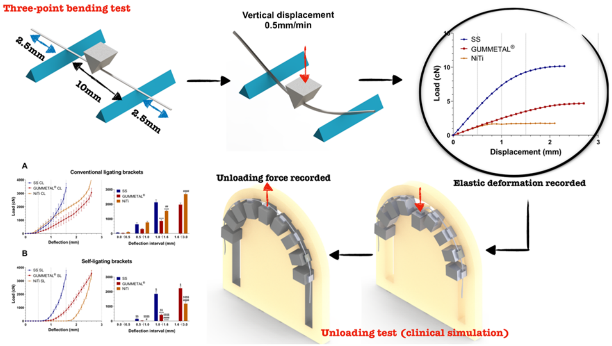
Abstract

A recently developed orthodontic wire alloy known as GUMMETAL® is claimed to deliver more physiological forces to correct dental mispositioning. However, its mechanical characteristics have not been fully characterized yet. This study aimed to determine and compare the elastic properties of different wire alloys, such as nickel–titanium (NiTi), stainless steel (SS), and GUMMETAL®, and assess their unloading forces when combined with either conventional or self-ligating brackets (CL and SL) when correcting dental crowding. All wires had a 0.016″ cross-section diameter. A three-point bending test was performed to assess the maximum deflection of each wire. Then, a subsequent analysis measured the unloading force for each wire/bracket system in a dental crowding clinical simulation device. The test was carried out in a universal testing machine with a cross-speed displacement of 0.5 mm/min. Data were recorded in different ranges and statistically evaluated using two-way analysis of variance. GUMMETAL® displayed higher unloading mean forces in SL brackets (2228.78 cN) than CL brackets (1967.38 cN) for the 1.6–3.0 deflection interval ($p = 0.018$). Within this interval, NiTi showed higher forces when used with CL brackets (2683.06 cN) than with SL brackets (1179.66 cN) ($p < 0.0001$). For the CL bracket systems, SS wires showed higher forces (2125.31 cN) in the 1.0–1.6 deflection interval than the other two wire alloys (NiTi, 1541.52 cN and GUMMETAL®, 852.65 cN) ($p < 0.0001$). SS wires also displayed lower forces with SL brackets (1844.01 cN) than in CL brackets (2125.31 cN) ($p = 0.049$). Thus, only GUMMETAL® revealed to be an optimal choice for SL brackets, whereas NiTi for CL brackets.

Graphical Abstract



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1 Introduction

The orthodontic tooth movement (OTM) concept regards the alveolar bone (re)modeling, which may be derived by the applied forces of mechanical forces through orthodontic appliances, composed of brackets and wires [1, 2]. The frequency and magnitude of orthodontics forces must be considered to determine the appropriate biomechanics for each patient's bone condition [3, 4], although the concept of an optimal force has been on debate for the past 80 years.

Forces under the optimal level cause no periodontal ligament reaction in which no tooth movement occur; on the other hand, overloading might lead to tissue necrosis, which prevents frontal bone loss. Thus, OTM cannot occur until resorption has eliminated the necrotic tissue [5, 6].

Several orthodontic appliances and wire materials are commercially available to optimize treatment, but the correct selection of the bracket design or wire alloys is left to the clinician, as different friction and elastic properties are essential to achieve a controlled movement during tooth movement [1, 2]. Nickel–titanium (NiTi) orthodontic wires (50% nickel and 50% titanium) are currently indicated for the initial leveling and alignment stages of orthodontic treatment due to the material's high elastic limits and resilience, and a low modulus of elasticity [7]. However, because NiTi wires are not shapeable, undesirable OTM may occur [8]. After the leveling stage, more robust materials, such as stainless steel (SS) or a titanium-molybdenum alloy (TMA), are typically used, as they are easier to reshape and to make contact with the bracket; thus, improving torque control. However, these materials have to be manually bent, and if not correctly applied, periodontal ligament overloading, root resorption, and bone loss may occur [9, 10].

A new β-titanium (βTi) alloy, named GUMMETAL®, has been suggested to display more favorable biomechanical properties than other known wire material. This multifunctional βTi alloy, developed in 2003, has a β-type, body-centered, cubic crystal structure, composed of titanium–niobium–tantalum–zirconium (Ti-36Nb-2Ta-3Zr-0.3O) [7, 11, 12]. GUMMETAL® is made of biocompatible and nontoxic atomic elements, and it is claimed to possess ultra-high-strength, an ultra-low Young's modulus, high flexibility, superelasticity (without hysteresis) [11]. These GUMMETAL® mechanical properties make this alloy an ideal candidate for applying it during all phases of orthodontic treatment [13]. Additionally, GUMMETAL® possesses ultra-high-strength bendability and has a low friction coefficient between a bracket and its attached wire, enabling a continuous and smoothly applied loading force [13]. Considering its high mean resilience property, it can enable a wide range of tooth movement. Although this alloy appears to be promising for clinical use, scientific evidence regarding its effectiveness remains scarce and studies assessing GUMMETAL® performance in different brackets designs (i.e., self-ligating, SL, or conventional ligating, CL) have not been previously performed.

The demand for this wire by orthodontic professionals has continuously grown, although the effectiveness of GUMMETAL® for aligning crowded teeth has not been scientifically explored, nor comparisons have been made when using this alloy with metallic CL and SL brackets. During OTM, wires are deflected due to the misalignment of the dental position.

The ability of a deflected wire to move the tooth into an optimal position is known as the unloading force, during crowding correction. Besides the wire elastic property, tooth movement may be influenced by the friction between wire and bracket, as well as the brackets' design. If this deflection surpasses the alloy's elastic limit, no alignment will occur.

Previous studies have characterized βTi alloys; however, GUMMETAL® has been recently introduced for orthodontic purposes. Due to the absence of scientific data that include the newer βTi classes, the aims of this in vitro study were to determine property of GUMMETAL® and compare to other alloys (i.e., NiTi and SS) and assess their unloading forces when used in combination with CL and SL brackets when correcting dental crowding.

2 Materials and methods

2.1 Experimental design

This study was divided into two phases (Fig. 1). First, the maximum deflection of each wire alloy was assessed: SS and NiTi from 3 M Unitek (California, USA) and GUMMETAL® from Rock Mountain Morita Corporation (Tokyo, Japan); in which a three-bending test was performed for three different wire materials [14–16]. All wires had the same circular cross-section diameter (0.016″).

The elastic limit was used as a reference to initially deform the archwires in the second section of this study, in which the bracket-wire combination design was tested in a dental crowding simulation. This clinical simulation device was used with each wire material combined with either CL or an SL bracket system. The test was carried out using a universal testing machine with a 50 N loading cell underwater (37 °C). The wire was displaced, and the unloading force (i.e., the returning of the wire for the initial position) was measured.

2.2 Three-point bending test

A digital caliper (Mitutoyo, São Paulo, Brazil) was used to standardize a 30-mm length of the 0.016″ cross-section

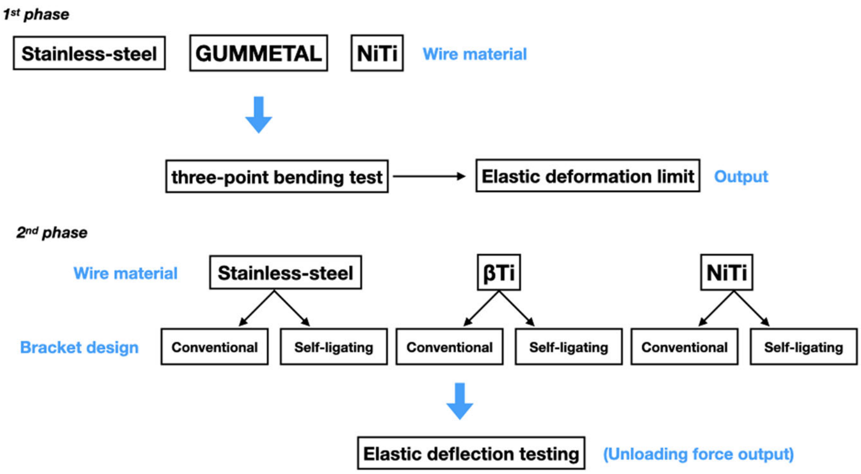

Fig. 1 Experimental design of the study. Initially, the elastic deformation limit of each wire material (SS, GUMMETAL, and NiTi) was characterized using a three-point bending test; these data were used as a reference for the second phase, where a clinical simulation device was used to simulate a dental crowding and measure the unloading force of each wire combined with a CL or SL bracket design

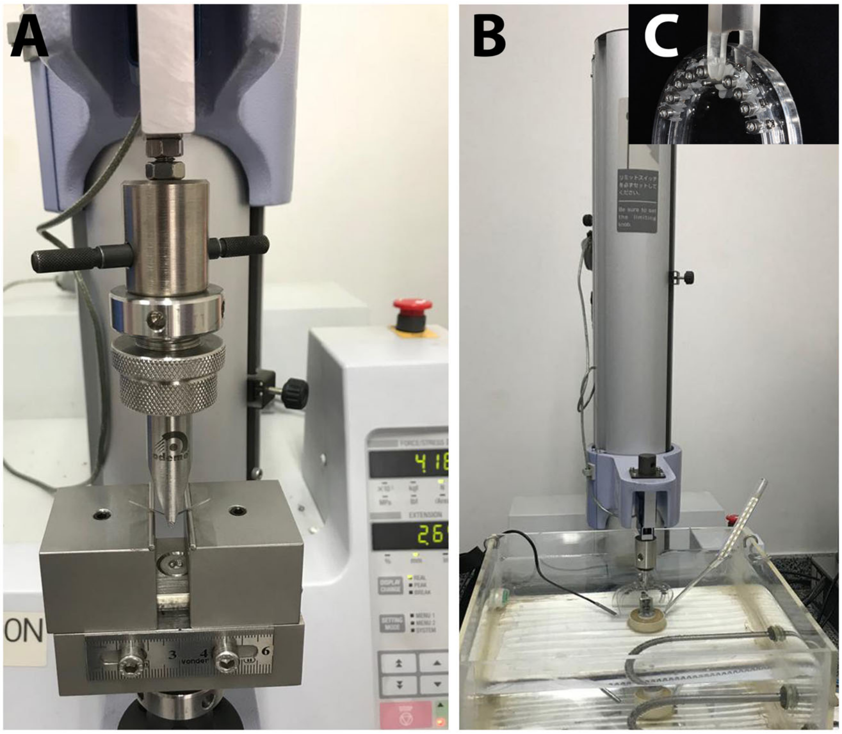

Fig. 2 Representative image of the experimental setups. **a** First study phase: the three-point bending test was performed in the EZ Test 500 N universal mechanical assay machine with the supports for the three points bending separated by 10 mm. **b** Second study phase: the clinical simulation testing setup. **c** The parabolic clinical simulation device, in which the tip of the activation element from the universal mechanical assay machine was positioned. The simulation device would have either a CL or SL bracket systems, and different archwire alloys attached for the different experimental assessments (Fig. 3)

diameter wires: SS, NiTi, and GUMMETAL®. Seven replicates of each type of wire were sectioned and mounted into the EZ Test 500 N universal mechanical assay machine (Shimadzu, Kyoto, Japan), into the supports for the three points bending, each separated by 10 mm (Fig. 2a). A triangular indenter was centrally positioned, and the test was performed at 0.5 mm/min vertical cross speed, using a universal testing machine, with a 50 N loading cell (Shimadzu, Kyoto, Japan). All test parameters and sample sizes were in accordance with ISO 15841:2007-01 (Dentistry—wires for use in orthodontics) [16]. The Shimadzu Trapezium 2 software (version 2.33, Shimadzu, Kyoto, Japan) was used to record the load force vs. displacement. The elastic limit was also recorded, to standardize the maximum preset deformation of each wire for the loading test.

2.3 Unloading test (clinical simulation)

The procedures used in this clinical simulation have been standardized and used previously [14–17]. The employed CL systems were Advanced brackets, Roth prescription (Orthometric®, São Paulo, Brazil), and the SL systems were DAMON® Q^{TM} brackets Ormco (Orange, USA).

CL or SL brackets were fixed onto a parabolic clinical simulation device, using cyanoacrylate glue (Superbonder, Loctite, São Paulo, Brazil). All brackets had 0.022″

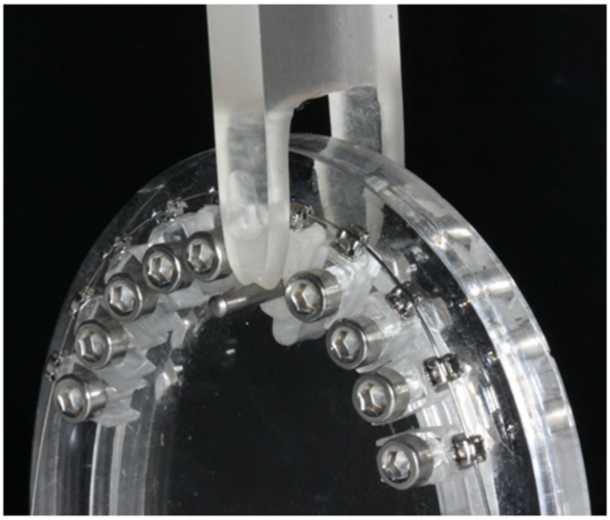

Fig. 3 Clinical simulation device where the central bracket was downward displaced based on the three-point bending output (−3 mm for GUMMETAL and NiTi and 1.6 mm for SS). The indenter was upward displaced, and the unloading force was recorded until the central bracket reached the initial position

(height) × 0.028″ (depth) dimensions and were vertically aligned using a 0.021″ (height) × 0.025″ (depth) SS archwire. Seven archwires (0.016″ cross-section diameter) of each alloy (i.e., SS, NiTi, or GUMMETAL®) were positioned onto CL and SL brackets. The wires were fixed onto CL brackets using Super Slick® Mini Stix Ligature Ties (TP Orthodontics; La Porte, Indiana, USA), with an outer diameter of 3.23 mm, using conventional methods (i.e., "O" shaped). The apparatus was immersed in water, at 37 ± 2 °C, and positioned into the EZ Test 500 N universal mechanical assay machine, with a 50-N cell load connected.

The tip of the activation device was positioned into the structure represented by the maxillary first central incisor, which could be moved along the buccolingual direction (Figs. 2b, c and 3).

The loading force and displacement values were set to zero, and the indenter was positioned into the cylinder and vertically displaced by 3 mm, for GUMMETAL® and NiTi archwires, and by 1.6 mm, for the SS archwires, according to the results obtained from the three-point bending test of the first phase of this study. The indenter was displaced upwards, at a 0.5 mm/min cross speed, and the unloading force was measured. The Shimadzu Trapezium 2 software recorded unloading forces (cN) vs. displacement (mm).

2.4 Statistical analysis

Data were analyzed using IBM SPSS, version 20 (New York, USA). Sample size was $n = 7$, all measurements were divided into four classes (0.0–0.5; 0.5–1.0; 1.0–1.5/1.6; 1.5/1.6–3.0), and the Kolmogorov–Smirnov normality test was applied. A two-way analysis of variance was used to assess significant differences between the effects observed among the tested materials and bracket systems. Data are plotted as the mean ± standard error of the mean, and statistical significance was set to 5% for all analyses. Graphs were constructed in GraphPad Prism 8.0 (California, USA).

3 Results

3.1 GUMMETAL® deforms more uniformly than other tested wire materials

Figure 4a shows the load (cN) vs. displacement (mm) curve for each wire during the tree-bending test; Fig. 4b shows the mean load for each range. For statistical purposes, the displacements induced in each alloy were divided into four different intervals. For the 0.0–0.5 displacement interval, a higher loading charge was required to significantly deform the SS wires (2.00 cN) when compared with the GUMMETAL® (0.65 cN) and NiTi wires (0.62 cN). In the higher displacement intervals, SS still required higher forces to be deformed, and GUMMETAL® also needed higher loading charges when compared to NiTi. These tendencies could be observed until the 1.5–3.0 displacement interval (SS, 9.89 cN; GUMMETAL®, 4.33 cN; and NiTi, 1.75 cN).

The curves, shown in Fig. 4a, demonstrate that NiTi wires deform while delivering lower loading forces, with a concise linear pattern (0.0–0.5 displacement). SS wires, in contrast, are characterized by a more significant reaction force, especially for the lower displacement range (0.0–1.0), and possess a broader linear range. GUMMENTAL® also deforms uniformly but delivered lower forces compared to SS.

3.2 GUMMETAL® reveals different force distribution behaviors between bracket systems

Figure 5 shows the unloading forces applied by the different archwire materials during different deflection ranges when combined with either CL (Fig. 5a) or SL (Fig. 5b) bracket systems. In this particular study, higher forces and lower friction were viewed as positive characteristics for the ability to reverse dental crowding [18, 19].

When using CL brackets, NiTi archwires displayed higher unloading forces in the 1.6–3.0 deflection interval (2683.06 cN). This particular interval was assessed for SS wires, which did not achieve deflections of this magnitude, based on the results of the three-point bending test. Additionally, the NiTi archwires achieved higher unloading forces then GUMMETAL® archwires for the 1.0–3.0 range. From 1.0 to 1.6 range SS, 2125.31 cN; NiTi, 1541.52 cN; and GUMMETAL®, 852.65 cN. From 1.6 to 3.0 range; NiTi, 2683.06 cN; and GUMMETAL®, 1967.38 cN. The SS

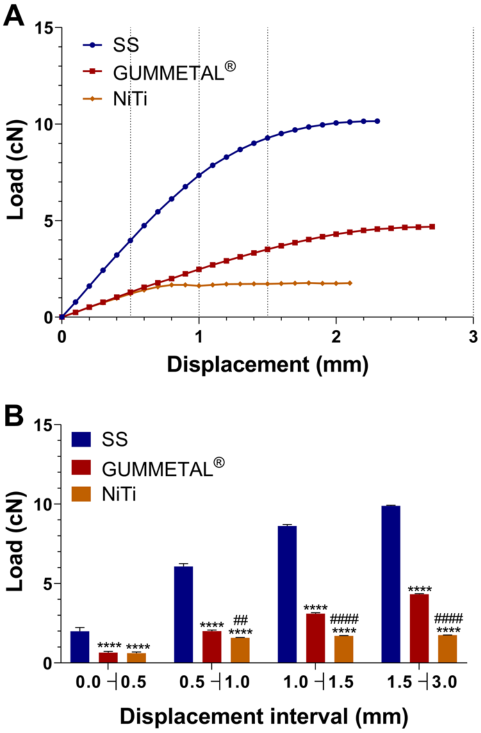

Fig. 4 SS requires higher forces for deformation, whereas GUMMETAL® reveals a displacement uniformity. The three-point bending test results, in which **a** the charges vs. displacements for each alloy are plotted. **b** Statistical comparisons between each wire material. $^{****}p <$ 0.0001 SS vs. GUMMETAL® or NiTi; $^{\#\#}p < 0.01$, $^{\#\#\#\#}p < 0.0001$ GUMMETAL® vs. NiTi

archwires only displayed an optimal performance for a very short deflection range (1.1–1.6).

The results for the SL bracket systems differed from those for the CL brackets. GUMMETAL® displayed higher unloading charges in SL brackets (2228.78 cN) than in CL brackets (1967.38 cN) for the 1.6–3.0 deflection interval; for the same range, NiTi showed higher forces when used in the CL brackets (2683.06 cN) than when used with the SL brackets (1179.66 cN). For the CL bracket systems, SS archwires imposed the highest forces (CL, 2125.31 cN) in the 1.0–1.6 deflection interval than the other two wires (NiTi, 1541.52 cN; and GUMMETAL®, 852.65 cN). SS archwires also displayed lower forces in SL brackets (1844.01 cN) than in CL brackets (2125.31 cN). However, the most interesting aspect observed when SL systems were combined with GUMMETAL® was the linear display of forces exhibit by the archwires in the deflection range from 0.8 to 2.6 (Fig. 5b).

4 Discussion

The elastic properties of orthodontic wires have improved as newer alloys have been developed. SS wires can be molded and deliver low friction; however, they are unable to achieve high degrees of deformation before reaching their elastic limit [20, 21]. These findings corroborate with the results of the present study, where SS showed a 1.6 mm deflection limit during the three-point bending representing the most rigid alloy tested. The NiTi and GUMMENTAL® showed 3 mm of displacement, keeping within the elastic bound and indicating higher elastic properties than SS [22, 23].

To overcome these limitations, NiTi wires were developed; they are superelastic and deliver lower forces given the same deformation and have low moldability [24, 25]. This behavior suggested the use of NiTi alloys at the beginning of orthodontic treatments to promote dental alignment, followed by SS wires used for the intermediary and final phase of tooth alignment. Changing wires during orthodontic treatment increases costs and also overall treatment time; additionally, the order of which archwires alloys to employ relies solely on professional experience. The use of GUMMETAL®, a specific type of βTi, has been proposed as a new alloy for orthodontic purposes due its high elasticity, moldability, and low rigidity [11, 26]; this wire seems to have the most remarkable mechanical properties described for an orthodontic wire making it suitable for use during all treatment phases [11].

In the second phase of this study, it was investigated how the different wire alloys interacted with different bracket systems. SL brackets were developed as an alternative for CL systems, to reduce the friction between the bracket and the wire, which is more biomechanically favorable for the teeth and periodontium [27]. Additionally, SL brackets seem to induce less biofilm retention and apply lower force levels than CL brackets, however, both brackets systems are still under a matter of discussion [28–30].

According to the results of the clinical simulation assay, GUMMETAL® has shown a more linear unloading behavior when connected to SL than the CL bracket system. Figure 5b showed that GUMMETAL® delivered unloading forces from 0.5 to 3.0 mm of deflection range following a linear pathway, indicating that it could be suitable for use from small (0.5 mm) to 3.0 mm dental crowding corrections. Nevertheless, NiTi only provided unloading forces from 1.6 to 3.0 mm, which limits its use for more pronounced crowding occurrences. Lastly, SS delivered forces from 0.5 to 1.6 mm, limiting its use to small corrections.

The more continuous and smoother behavior of GUMMETAL® could be attributed to its lower bending elastic modulus, bending strength, and fatigue limit [31]. Once GUMMETAL® has high mean resilience, which represents the energy storage capacity combined to its strength and elasticity, it is more suitable to achieve a wide ranging of tooth movement compared with the other alloys [31]. Additionally, since GUMMETAL® is nickel free, it can be used as an alternative material for patients who have nickel

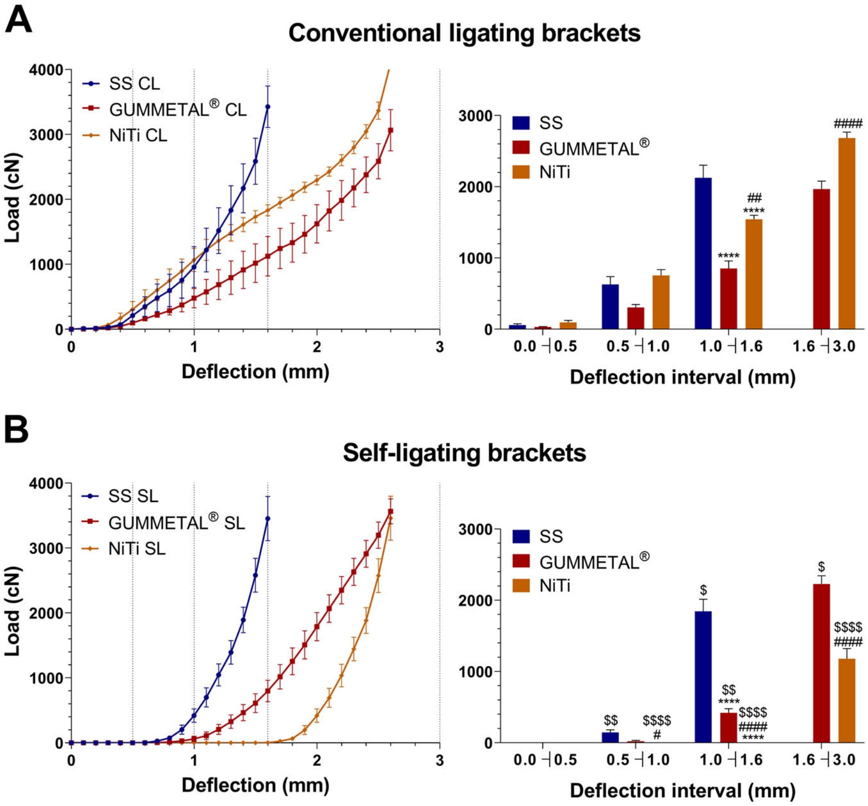

Fig. 5 Unlike SS or NiTi archwires, GUMMETAL® shows distinct force behaviors in different bracket systems. The clinical simulation test was performed to compare unloading forces vs. deflections in teeth when using different wire materials with either **a** CL or **b** SL bracket systems. $^{****}p <$ 0.0001 SS vs. GUMMETAL® or NiTi; $^{\#\#}p < 0.01$, $^{\#\#\#\#}p < 0.0001$ GUMMETAL® vs. NiTi; $^{\$}p <$ 0.05, $^{\$\$}p < 0.01$, $^{\$\$\$\$}p < 0.0001$ CL vs. SL

allergy [7, 31]. These results are in accordance with Murakami et al. [31], which reported a continuous light force delivery for GUMMETAL® compared to TMA and Resolve, both βTi-derived alloys. This plastic behavior without crystal motion dislocation occurs due to oxygen addition and proper cold working [11, 12, 32]. In contrast, GUMMETAL® delivered lower unloading forces than NiTi and SS when combined with CL brackets; these might be attributed to a wire-bracket interaction, mainly due to the high friction achieved by the ligatures [33].

Considering the CL bracket system, the results of this study suggest that NiTi archwires are more suitable to be applied during the initial stages of dental crowding correction since it delivers higher and continuous unloading forces, from 0.2 to 3.0 mm range than GUMMETAL®. Additionally, SS archwires could potentially be applied during a later phase of treatment; however, its application may be limited as it may be adequate for dental deflections of up to 1.6 mm due to its rigid characteristic [33].

This study was limited to evaluate a single wire circular cross-section diameter (i.e., 0.016″). No rectangular cross-section or additional alloys were considered; no TMA wires were included for comparisons since they were not commercially available at the same 0.016″ cross-section diameter. Although GUMMETAL® seems to have promising mechanical advantages, it still has a higher cost than other alloys. Moreover, its worldwide reach is still limited.

The literature is still lacking scientific evidence for GUMMETAL® uses; this study has provided insights regarding the mechanical response by this new alloy proposed for orthodontic use, and compared to other well-known alloys (i.e., SS and NiTi). Nevertheless, this study used a controlled clinical simulation tested underwater. Future randomized clinical trials are necessary to confirm these findings and support its safe use as well as the periodontium biological response.

5 Conclusions

Based on the results of the clinical simulation testing, NiTi appears to be the most appropriate alloy for use in combination with CL systems, whereas GUMMETAL® appears to be best suited for use with SL brackets for dental crowding correction. Both NiTi and GUMMETAL wires have shown elastic property up to a 3 mm deflection, while SS was limited to 1.6 mm.

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Author contributions ACRN-S, MBN, LTS, ACK, DB, and MM collected data. HDPS performed data curation. MCS acquired funds and resources. PMC provided a critical analysis of the data. ACRN-S and EL drafted and revised the paper. All authors approved the final version of this document.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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