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ORIGINAL ARTICLE

Mechanical properties of different esthetic and conventional orthodontic wires in bending tests

An in vitro study

Mechanische Eigenschaften verschiedener ästhetischer und konventioneller kieferorthopädischer Drähte in Biegeversuchen

Eine In-vitro-Untersuchung

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Abstract

Aims The goal of this study was to determine the mechanical properties of different esthetic and conventional orthodontic wires in three-point and four-point bending tests, and in a biomechanical test employing three bracket systems.

Methods The behavior of round wires with a diameter of 0.46 mm (0.018″) were investigated: uncoated nickel titanium (NiTi) wires, surface modified NiTi wires; FLI® Orthonol Wire® and glass fiber reinforced plastic wires. The biomechanical bending test was performed using the following bracket types: metal brackets (Discovery®, Dentaurum), ceramic brackets (Fascination®, Dentaurum), and plastic brackets (Elegance®, Dentaurum). All bending tests were performed in the orthodontic measurement and simulation system (OMSS) at a temperature of 37 °C. The classical three-point bending test was performed according to an ISO standard (DIN EN ISO 15841:2007) using the appropriate thrust die and supports with a predefined span of 10 mm. In the other tests the supports or interbracket distances were chosen such that the free wire length was also 10 mm (5 mm between adjacent brackets). All wires were loaded centrally to a maximum of 3.1 and 3.3 mm in the biomechanical test, respectively. The force was measured upon unloading with a loading velocity of 1 mm/min. Each specimen was loaded twice and a total of 10 specimens tested for each product. Weighted means and the error of the weighted mean were calculated for each product.

Results Fiber reinforced wires displayed lowest forces in three-point bending with values of 0.4 N at a displacement of 1 mm and 0.7 N at a 2 mm displacement. In four-point bending the forces were 0.9 N and 1.4 N, respectively, at the same displacements. Almost all of the translucent wires showed fracture upon bending at displacements greater than 3 mm, independent of the bending test and bracket type. The different investigated NiTi wires, surface modified or conventional, only showed minor variation, e.g., 2.2 N for rematitan® Lite White and 2.0 N for rematitan®, 2.1 N for FLI® Coated Orthonol® and 1.7 N for Orthonol® in four-point bending. The rhodinized wire generated forces between these values (2.1 N).

Conclusion The translucent wires had the lowest forces in all three bending tests; however, displacements above 3 mm resulted in increased risk of fracture. Forces of investigated NiTi wires were very high and in part above clinically recommended values.

Keywords Orthodontic wires · Nickel titanium · Surface modification · Mechanical properties

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Zusammenfassung

Ziele Ziel der Studie war es, die mechanischen Eigenschaften verschiedener ästhetischer und konventioneller kieferorthopädischer Drähte in unterschiedlichen Biegeversuchen zu bestimmen: im klassischen Dreipunkt-Biegeversuch und im Vierpunkt-Biegeversuch, aber auch in einem biomechanischen Biegeversuch unter Einsatz von 3 Brackets.

Methoden Die Eigenschaften folgender Runddrähte mit einem Durchmesser von 0,46 mm (0.018″) wurden untersucht: unbeschichtete Nickel-Titan(NiTi)-Drähte (rematitan® Lite, Dentaurum; Orthonol®, RMO), oberflächenmodifizierte NiTi-Drähte (rematitan® Lite White, Dentaurum; Plated Esthetik, rhodinized, Dentalline; FLI® Wire Orthonol®, RMO) und glasfaserverstärkte Kunststoffdrähte (transluzenter Bogen pearl, Dentaurum). Für den biomechanischen Biegeversuch wurden verwendet: Metall- (Discovery®, Dentaurum), Keramik- (Fascination®, Dentaurum) und Kunststoffbrackets (Elegance®, Dentaurum). Alle Biegeversuche wurden im orthodontischen Mess- und Simulationssystem (OMSS) bei einer Temperatur von 37 °C durchgeführt. Der klassische Dreipunkt-Biegeversuch erfolgte nach der ISO-Norm (DIN EN ISO 15841:2007) unter Einsatz eines vorgeschriebenen Druckstempels und einem Abstand der Stützpunkte von 10 mm. In den anderen Versuchen wurden die Stützpunkte bzw. die Interbracketabstände so gewählt, dass sich ebenfalls eine freie Drahtlänge von 10 mm ergab (5 mm Abstand zwischen den benachbarten Brackets). Alle Drahtproben wurden zentral bis zu einer maximalen Auslenkung von 3,1 bzw. 3,3 mm für den biomechanischen Test belastet. Die Kraft wurde auf dem anschließenden Entlastungsweg bei einer Geschwindigkeit von 1 mm/min gemessen. Jede Probe wurde 2-mal belastet und es wurden von jedem Produkt 10 Proben gemessen, berechnet wurden gewichtete Mittelwerte und der Fehler des gewichteten Mittels.

Ergebnisse Glasfaserverstärkte Kunststoffbögen erzeugten im Dreipunkt-Biegeversuch mit 0,4 N bei einer Auslenkung von 1 mm und 0,7 N bei 2 mm die niedrigsten Kräfte. Im Vierpunkt-Biegeversuch lagen die Kräfte bei 0,9 und 1.4 N bei den entsprechenden Auslenkungen. Nahezu alle transluzenten Bögen zeigten Brüche bei der Biegeprüfung für Auslenkungen über 3 mm, unabhängig von der Art des Biegeversuchs und des verwendeten Brackettyps. Die unterschiedlichen untersuchten NiTi-Drähte zeigten, unabhängig von der Art der Oberflächenmodifikation bzw. davon ob beschichtet oder nicht, nur geringfügige Unterschiede in ihrem Kraftniveau. So erzeugten z. B. der rematitan Lite White 2,2 N und der rematitan 2,0 N, der FLI® Coated Orthonol® 2,1 N und der Orthonol® 1,7 N im Vierpunkt-Biegeversuch. Der rhodinierte Draht erzeugt vergleichbare Kräfte (2,1 N).

Schlussfolgerungen Der transluzente Bogen hatte die geringsten Kräfte in allen 3 Biegeversuchen, jedoch zeigte er bei Auslenkungen über 3 mm eine verstärkte Bruchneigung. Die Kräfte der untersuchten NiTi-Drähte waren sehr hoch und teils oberhalb der klinisch empfohlenen Werte.

Schlüsselwörter Kieferorthopädische Drähte · Nickel-Titan · Oberflächenmodifikation · Mechanische Eigenschaften

Introduction

The patients' demand for brackets and wires with improved esthetic characteristics has increased significantly in recent years. These brackets and wires are almost invisible and most companies offer such wires in growing numbers. Coating materials and techniques differ significantly. Besides coated wires, wires made of glass-fiber-reinforced plastic, so-called translucent wires, are offered. With these materials manufacturers not only try to optimize the material characteristics, compared to metallic alloys, but also to improve aesthetics. First application of fiber-reinforced composites was permanent retention [9], but the low Young's modulus of these wires is interesting for the application of reduced forces, e.g., during leveling.

Various methods are described in the literature for the determination of the mechanical characteristics of orthodontic wires. Standards offer the user the chance to compare products under identical conditions with respect to their clinical requirements [22]. According to the original ADA (American Dental Association) Specification No. 32 from the year 1977, a cantilever bending had to be performed [1], while in the current version from 2000, a three-point bending test is to be performed [3]. In the international and German standard DIN EN ISO 15841:2007 the exact parameters for a three-point bending test of orthodontic wires are defined [10].

Besides cantilever and three-point bending, the four-point bending test might mimic the intraoral situation best, as the two central loading pins and the two supports represent the central, displaced bracket and the two neighboring brackets. The interbracket distance and the total free wire length can be varied, depending on the bracket width of the bracket system used. However, until now no study comparing the results from three-point or four-point bending tests with testing of orthodontic wires in a three-bracket arrangement has been published. Only one paper reports on measurements comparing bending in a three-bracket system and three-point bending [20]. However, only one superelastic wire was tested and no report with respect to esthetic and composite wires is known. Thus, it was the aim of this study to investigate the mechanical properties of various coated and uncoated as well as fiber-reinforced composite orthodontic wires in different bending tests, such as three- and four-point bending as well as bending in a multibracket arrangement.

Materials and methods

Wires

Bending tests were performed using conventional, uncoated nickel titanium (NiTi) wires, NiTi wires with various surface modifications, and glass-fiber-reinforced composite wires from different manufacturers. All wires had the identical cross-section of 0.46 mm (0.018″) that it is mainly used at the end of the levelling stage and before further stages of orthodontic treatment may be contemplated. Using lower size wires may not represent differences in bracket geometry due to the large play between the wire and bracket slots. In addition, the translucent wires are only available in 0.018″ size so matching size in the NiTi was used for reasonable comparison. All wires are listed in Table 1 together with manufacturer information, material composition and surface modification, reference number, and short code for identification.

Brackets

The bending test employing brackets was performed using standard edgewise bracket systems of the 0.022″ slot system: conventional metal brackets, glass-fiber-reinforced composite brackets, and ceramic brackets. Ligation was performed with elastic ligatures. All materials are listed in Table 1, again together with manufacturer information, material composition, reference number, and short code.

Experimental set-up and procedure

All bending tests were performed using the Orthodontic Measurement and Simulation System (OMSS) at a temperature of 37 °C. The set-up consists of two measurement tables, each equipped with a six-axis positioning stage and a six-component force/torque transducer [5, 11]. The whole set-up is built into a temperature test chamber to enable experimentation at an ambient temperature of 37 °C, which is relevant for determining mechanical characteristics of orthodontic NiTi wires. For the bending tests only one measurement table was required and the different bending set-ups were integrated into the OMSS (Figs. 1, 2, 3).

The three-point bending tests were performed according to DIN EN ISO 15841:2007 [10]: The supports to define the free wire span had a distance of 10 mm and a total wire length of 30 mm was installed in the set-up. A central

Tab. 1 Compilation of the investigated arch wires and brackets together with manufacturer, material, order number, and short code for identification. All wires had a round cross section with a diameter of 0.46 mm (0.018″)

Tab. 1 Zusammenstellung der untersuchten Drähte und Brackets mit Angaben zu Hersteller, Material, Bestellcode und Kurzbezeichnung für die Identifikation. Alle Drähte hatten einen Durchmesser von 0,46 mm (0.018″)

Product Produktname	Manufacturer	Material	REF	Short Code
Translucent Ideal Arch pearl	Dentaurum	Glass fiber reinforced composite	766-906-00	DEtrans
Plated Esthetik NiTi Super Elastik	Dentalline	Rhodinized NiTi	163-071-81	DLrhoNiTi
rematitan® "LITE" White Ideal Arch	Dentaurum	Coated NiTi	768-016-00	DERMTW
FLI® Wire Orthonol® Superelastic	RMO	Coated NiTi	A07002-A	RMOORF
rematitan® "LITE" Ideal Arch	Dentaurum	Conventional NiTi	766-066-00	DERMTL
Orthonol® Superelastic Nickel-Titanium	RMO	Conventional NiTi	A07022	RMOORS
discovery® Brackets Standard Edgewise 22	Dentaurum	Conventional metal bracket	722-205-01	DEdisc
Elegance® Brackets Standard Edgewise 22	Dentaurum	Glass fiber reinforced composite bracket	791-065-00	DEEleg
Fascination® Ceramic Brackets Standard Edgewise 22	Dentaurum	Ceramic bracket	700-066-03	DEFasc
Dentalastics® Personal Sortiment, White	Dentaurum	Elastic ligature	774-561-01	

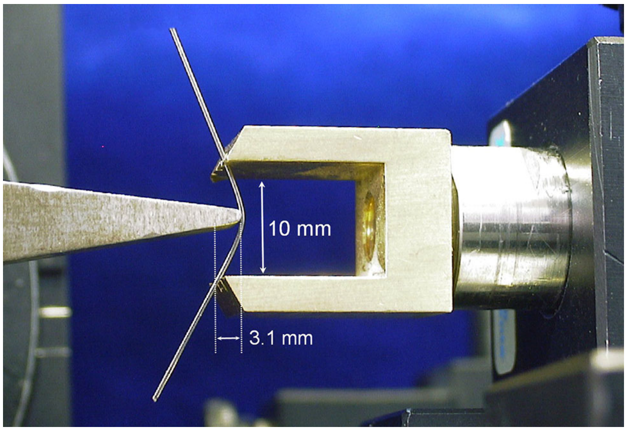


Fig. 1 Three-point bending test according to DIN EN ISO 15841 [10] in the OMSS. A wire segment of 30 mm is inserted and displaced to a maximum of 3.3 mm. The forces are registered upon unloading at predefined points
Abb. 1 Dreipunkt-Biegeversuch nach DIN EN ISO 15841 [10] im OMSS. Ein Drahtsegment der Länge 30 mm wird eingelegt und bis zu einer maximalen Auslenkung von 3,3 mm belastet. Die Kräfte werden an definierten Punkten auf den Entlastungsweg gemessen

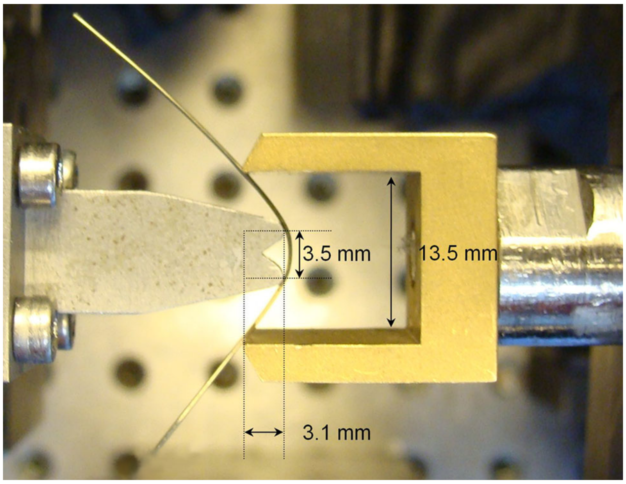


Fig. 2 Four-point bending test in the OMSS. The test geometry and free wire length is similar to the three-point bending from Fig. 1
Abb. 2 Vierpunkt-Biegeversuch im OMSS. Die Biegeanordnung und die freie Drahtlänge entsprechend dem in Abb. 1 dargestellten Dreipunkt-Biegeversuch

loading pin was placed opposite to the wire, such that it did not have contact (Fig. 1). Due to manufacturing reasons the pin had a defined radius of curvature of 0.3 mm, which is slightly above the dimension defined in the standard (0.1 ± 0.05 mm). But we do not assume an influence on the results by this minor deviation from the standard. The deflection of the wire was 3.1 mm and measurement of the force was performed upon unloading [10].

Basically, the four-point bending test also followed the standard instructions [10]. The twin loading pin had two individual knuckles with a radius of curvature of 0.3 mm each. The distance of the two tips was 3.5 mm and the distance of the supports 13.5 mm. Thus, the length of the wire between the outer supports was also 13.5 mm and due to the two knuckles of the loading pin having a distance of 3.5 mm a free wire span of the tested orthodontic wires of 10 mm resulted. The position of the supports and the knuckles of the loading pin were adjusted such that a free wire length of 5 mm on each side of the knuckles was realized (Fig. 2), i.e., the wire was loaded centrally. A total wire length of 30 mm was installed again and a central deflection of 3.1 mm was adjusted. Again, measurement of the force was performed upon unloading.

The bending test with the three-bracket arrangement was composed in a way that the interbracket distance between the two terminal brackets resulted in a free wire length of 10 mm, similar to the three- and four-point bending tests. As the brackets had widths between 3.3 and 3.5 mm, the position of the terminal brackets had to be adjusted accordingly (Fig. 3), i.e., the outer brackets were adjusted such that the wire length between them was between 13.3 and 13.5 mm, depending on the width of the central bracket. For example, a bracket with a width of 3.3 mm was combined with a total wire length of 13.3 mm, again resulting in a free wire length of 10 mm. The central bracket was fixed to a bracket adaptor instead of the loading pin. After careful adjustment and ensuring the free wire length left and right of the central bracket was 5 mm, the wire was ligated to the three brackets with elastic ligatures. In the neutral position the force sensor now recorded zero forces and torques. Subsequently, the central bracket was then moved independently in two directions, first along the intrusion/extrusion axis, similar to the pure bending tests and then in the vestibular/lingual direction. A displacement of 3.3 mm was chosen to ensure that the wire was on the unloading plateau when a deflection of 3.0 mm was reached upon deactivation. Forces were recorded again on the unloading path.

A total of ten specimens were measured for each wire product and type of measurement. A new wire segment was cut from a rather straight part of an orthodontic arch wire for each measurement. Each individual wire measurement was repeated twice to check for reproducibility of the superelastic curves. The force values were extracted from the force/displacement curves at 2 and 1 mm deflection on the unloading path. The weighted mean and the error of the weighted mean were calculated from the force values, using the standard deviation (SD) of the two consecutive measurements of each specimen as the weight.

Statistical analysis

Using the χ^2 test, all results were checked for normal distribution. As the different bracket/wire combinations did

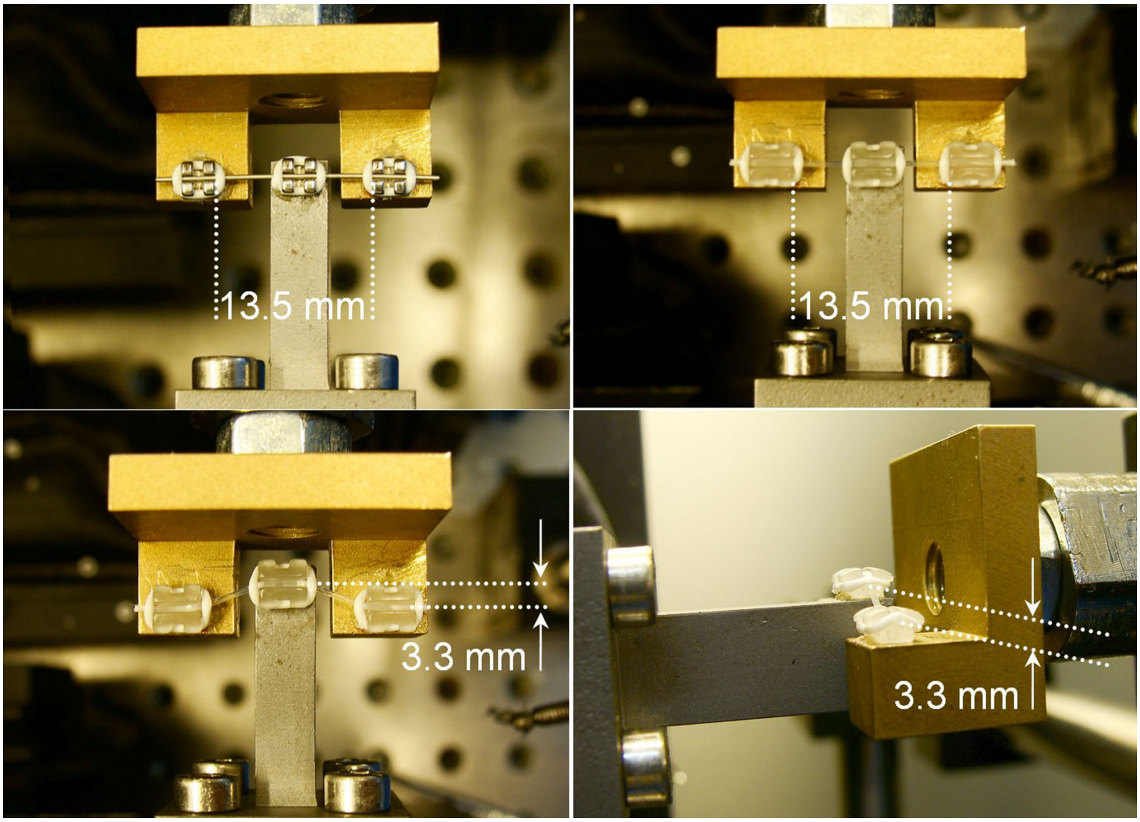


Fig. 3 Three-point bending test employing different brackets. The arrangement is such that a free wire length of 10 mm is ensured. The wire is deflected in intrusion and vestibular directions

Abb. 3 Dreipunkt-Biegeversuch unter Einsatz verschiedener Brackets. Die Anordnung ist so gewählt, dass sich eine freie Drahtlänge von 10 mm ergibt. Der Draht wird auf Intrusion und Vestibulärverlagerung belastet

not show normal distribution, the Mann–Whitney *U* test was used to check for statistical significance of differences and a Bonferroni correction was performed to account for multiple analysis. A value of $p < 0.05$ was chosen to prove significant differences. Statistical analysis was performed using the statistics package SPSS® for Windows (Version 22, IBM, Armonk, NY, USA) and graphics and statistics software Excel Version 2007 (Microsoft, Redmond, WA, USA).

Results

Figure 4 displays typical force/deflection curves of the measured wires in three-point bending. As wire measurements were repeated twice, two curves are displayed for each specimen in the individual graphs. The arrows indicate the loading and the unloading branches. Obviously, the specimen of the glass-fiber-reinforced wire fractured at a deflection around 2 mm (marked by the circle) resulting in a very low, yet still active force upon unloading of the first unloading cycle and the complete second loading cycle. All NiTi wires showed a superelastic behavior with a hysteresis and higher forces on the loading than on the unloading path. Nevertheless, the curves differed in shape and delivered slightly varying forces at the measurement points of 2 and 1 mm.

Figure 5 shows force/deflection curves as measured in the biomechanical test using the discovery bracket with an elastic ligature. Figure 5a displays the curves upon loading in the intrusion direction, Fig. 5b the forces upon protrusion. The forces upon intrusion (Fig. 5a) are slightly higher than in three-point bending and the hysteresis curves of the NiTi wires are broader. This may be explained by the friction effect in the system: Upon loading, friction slightly increases the force, as it hinders the free sliding through the bracket slots. Upon unloading, the force is reduced, as the wires do not slide back freely and the pressure on the loading tip is reduced. Again the translucent wire shows a fracture at roughly 2 mm (marked by the circle). All curves in Fig. 5b look similar. Even the translucent wire seems to have a plateau and it does not show fracture. Obviously in this load mode we only measure the activation of the elastic ligature, resulting in almost similar forces for all wires. The hysteresis results from the friction in the system and the NiTi wires almost do not enter the plateau

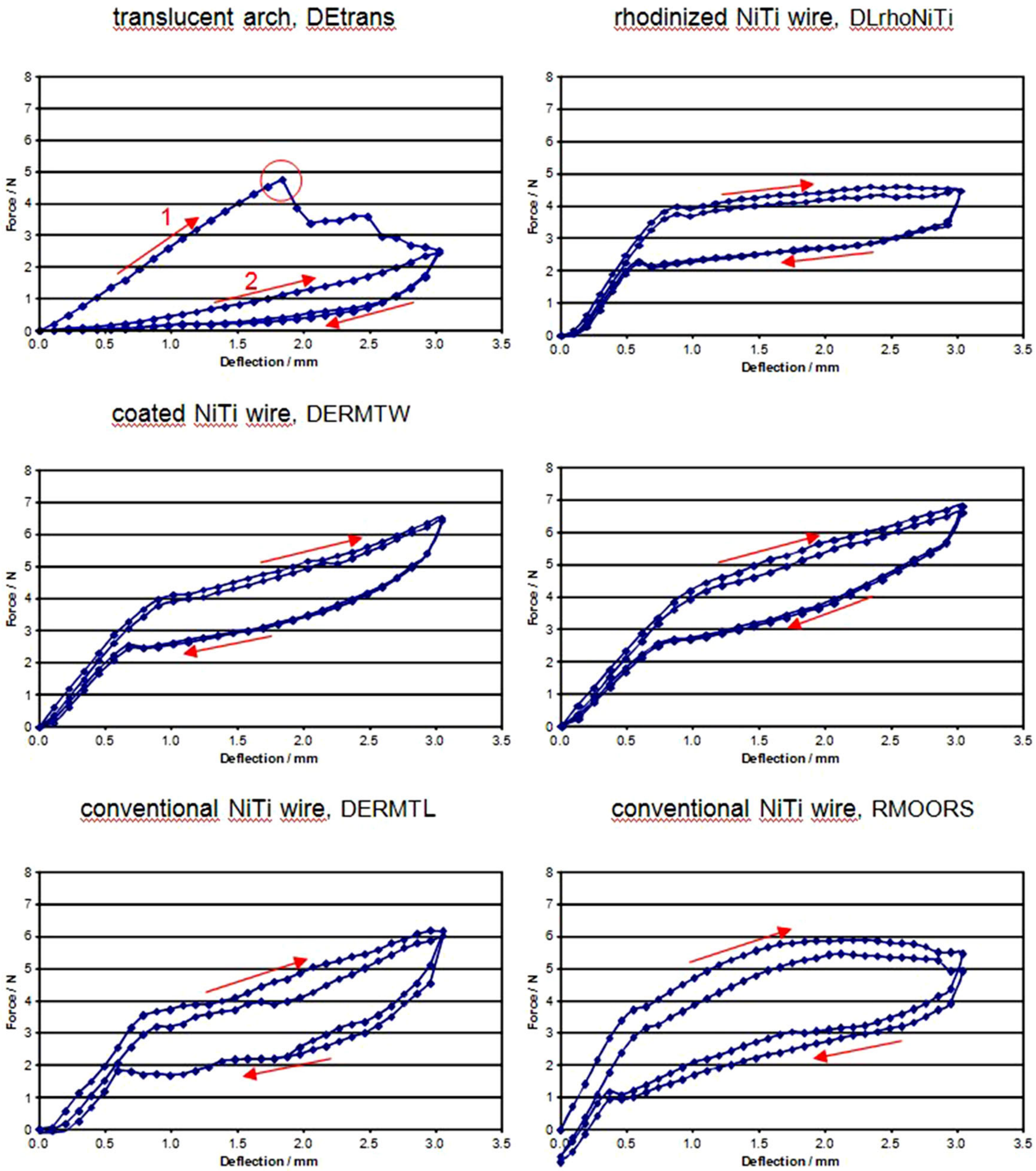


Fig. 4 Force/deflection diagrams in three-point bending. The wire types are labeled above each curve. As each sample was loaded twice, two loading/unloading curves are displayed for each wire. The *arrows* indicate the loading and unloading branches. Obviously this sample of the composite wire showed a fracture below 2 mm deflection (marked by the *circle*). Thus, the second loading cycle (*2*) runs with a clearly lower slope than the first one (*1*). The hysteresis curves of the NiTi wires show characteristic differences but do not differ in forces significantly

Abb. 4 Kraft/Auslenkungskurven im Dreipunkt-Biegeversuch. Die Drähte sind oberhalb der Kurven gekennzeichnet. Da jede Probe 2-mal in Folge belastet wurde, sind jeweils 2 Kurven je Draht dargestellt. Die *Pfeile* zeigen die Belastungs- und Entlastungsäste an. Offensichtlich zeigte diese Probe des Kompositdrahts einen Bruch bei einer Auslenkung von 2 mm (durch den *Kreis* markiert). Die zweite Belastung (*2*) verläuft daher mit einer deutlich reduzierten Steigung als die erste (*1*). Die Hysteresekurven der NiTi-Drähte zeigten charakteristische Unterschiede, unterschieden sich aber in der Kraft nicht wesentlich

behavior, explaining the similarity of the curves of the translucent and the NiTi wires. The behavior of the Elegance® and Fascination brackets was similar, especially in protrusion direction.

Figure 6 summarizes the forces on the unloading path for all wires and bending tests at deflections of 1 mm (Fig. 6a) and 2 mm (Fig. 6b) upon unloading. Except for the three-point bending test only minor differences are

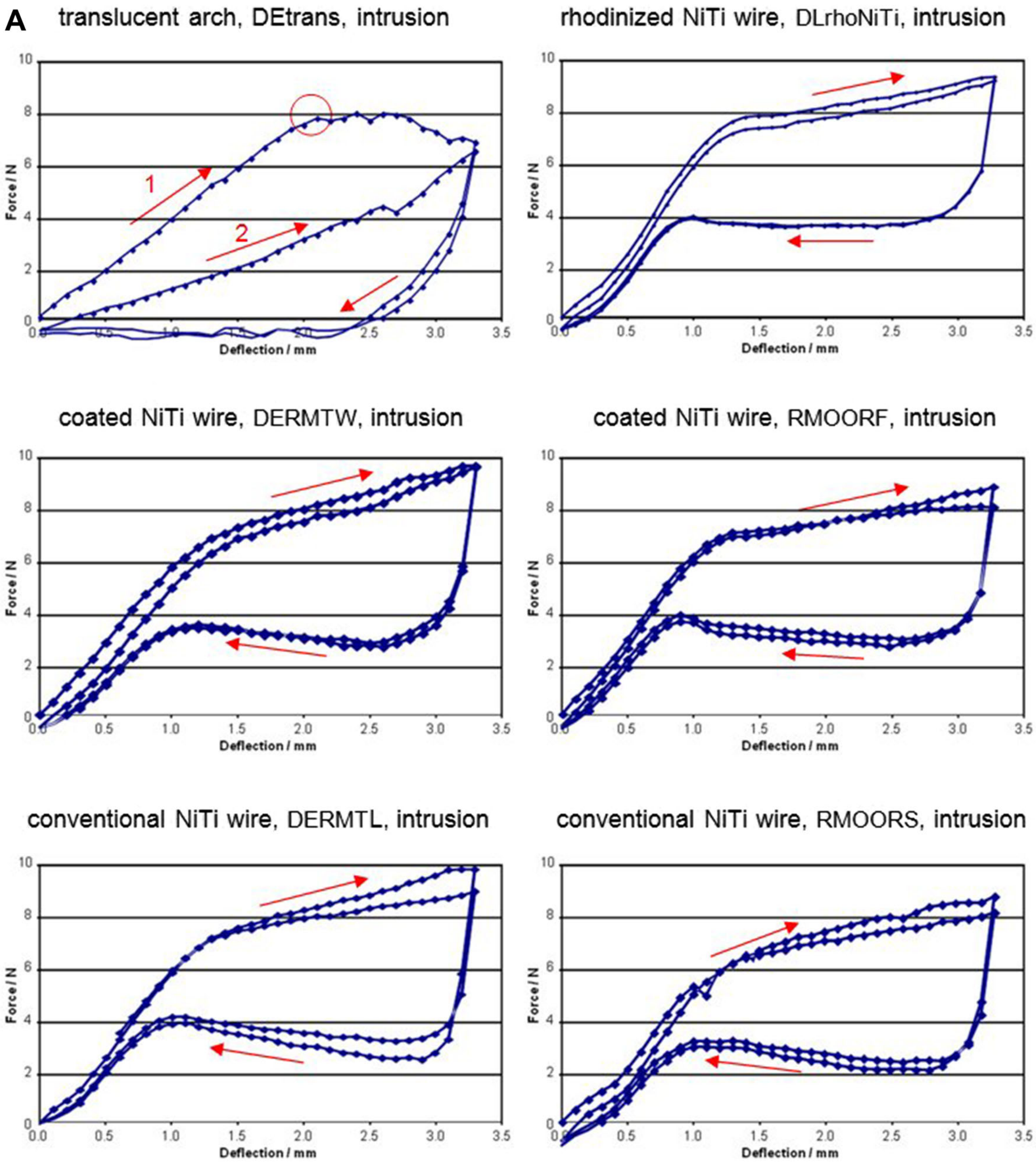
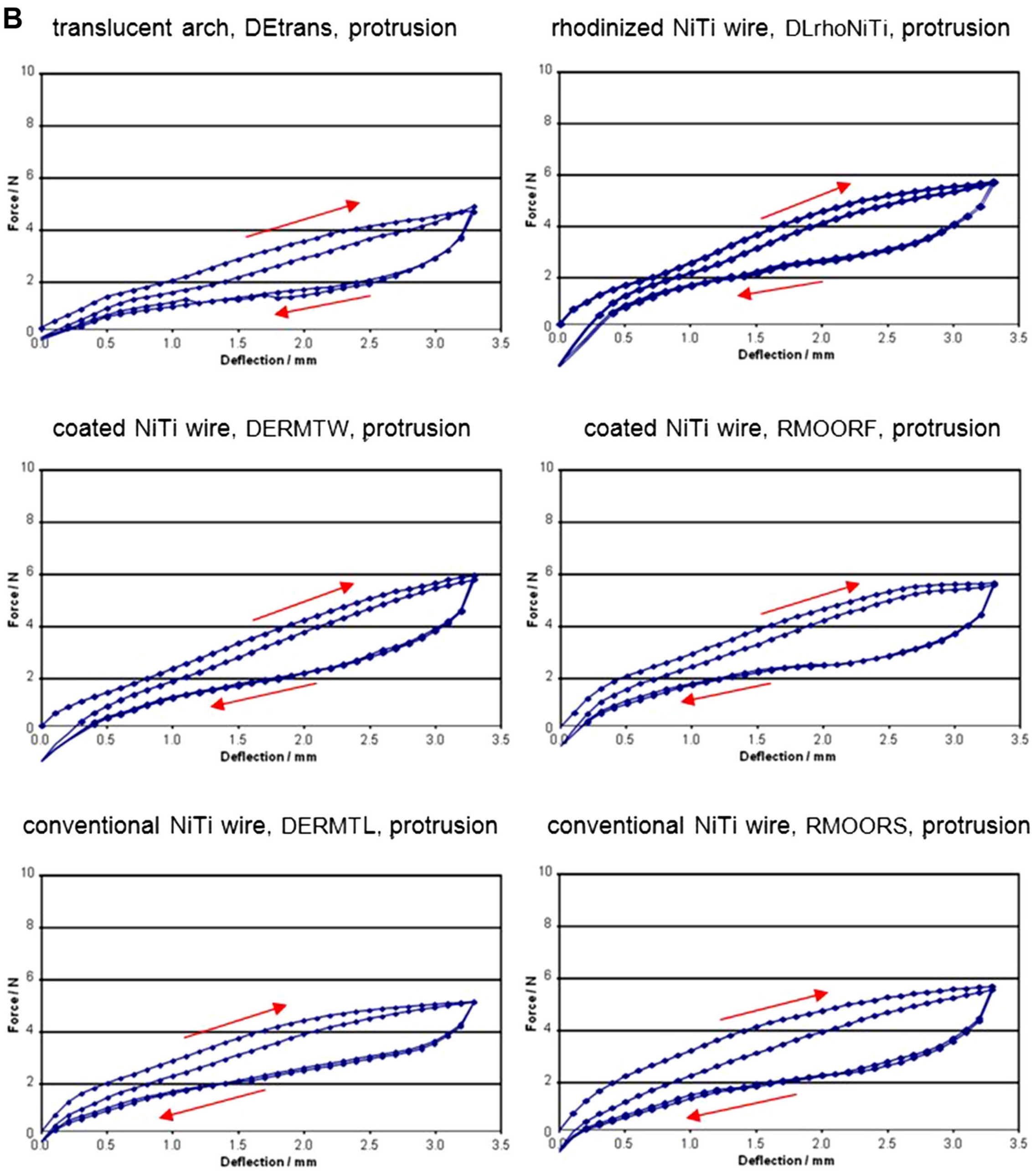


Fig. 5 **a** Force/deflection diagrams in biomechanical testing with three brackets. The movement of the central bracket simulated an intrusion of up to 3.3 mm. Same notations as in Fig. 4. Again, two loading/unloading curves are displayed for each wire. The *arrows* indicate the loading and unloading branches. Obviously this sample of the composite wire showed a fracture at 2 mm deflection (marked by the *circle*) and the second loading cycle (*2*) runs with a clearly lower slope than the first one (*1*). The hysteresis curves of the NiTi wires show characteristic differences but do not differ in forces significantly. **b** Force/deflection diagrams in biomechanical testing with three brackets, however, simulating a protrusion of up to 3.3 mm. Same notations as before. This composite wire did not fracture. The hysteresis curves of the NiTi wires are significantly reduced, compared to Figs. 4 and 5a. The elastic ligation seems to dominate the force/deflection behavior in this loading mode

Abb. 5 **a** Kraft/Auslenkungskurven im biomechanischen Versuch mit 3 Brackets. Die Bewegung des zentralen Brackets simulierte eine Intrusion von bis zu 3,3 mm. Die Bezeichnungen entsprechen denen aus Abb. 4. Dargestellt sind wiederum jeweils 2 Kurven je Draht. Die *Pfeile* zeigen die Belastungs- und Entlastungsäste an. Offensichtlich zeigte diese Probe des Kompositdrahts einen Bruch bei einer Auslenkung von 2 mm (durch den *Kreis* markiert) und die zweite Belastung (*2*) verläuft daher mit einer deutlich reduzierten Steigung als die erste (*1*). Die Hysteresekurven der NiTi-Drähte zeigten charakteristische Unterschiede, unterschieden sich aber in der Kraft nicht wesentlich **b** Kraft/Auslenkungskurven im biomechanischen Versuch mit den 3 Brackets bei Simulation einer Protrusion von bis zu 3,3 mm. Bezeichnungen wie in den vorherigen Abbildungen. Dieser Kompositdraht zeigte keinen Bruch. Die Hysteresekurven der NiTi-Drähte sind deutlich reduziert verglichen mit denen in Abb. 4 und 5a. Die elastischen Ligaturen scheinen das Kraft/Auslenkungsverhalten bei dieser Belastung zu dominieren



translucent arch, DEtrans, protrusion

rhodinized NiTi wire, DLrhoNiTi, protrusion

coated NiTi wire, DERMTW, protrusion

coated NiTi wire, RMOORF, protrusion

conventional NiTi wire, DERMTL, protrusion

conventional NiTi wire, RMOORS, protrusion

Fig. 5 continued

obvious. Lowest forces between 0.4 N (three-point bending) and 1.1 N (bending with the discovery bracket in vestibular direction) were generated by the glass-fiber-reinforced wire (Fig. 6a, 1 mm deflection). At a deflection of 2 mm (Fig. 6b), forces of the composite wire were slightly increased (between 0.5 and 1.9 N) but still the lowest in the whole group. All forces of the composite wire proved to be significantly different ($p < 0.05$) from all other wires in all bending tests and at both deflections. The further presentation of results thus concentrates on the characteristics of the different NiTi wires.

Except for the rematitan® wire, the differences between three-point and four-point bending are small. The reason for the high forces generated by rematitan® Lite and rematitan® white in three-point bending have to be discussed below. At the 1 and 2 mm deflection in intrusion direction, the forces using the bracket arrangements were slightly increased compared to the three-point and four-point bending tests. Obviously, all NiTi wires (coated or uncoated) generated almost similar forces that were higher than the forces produced by the composite wire. This held true for all types of bending tests and all bracket groups.

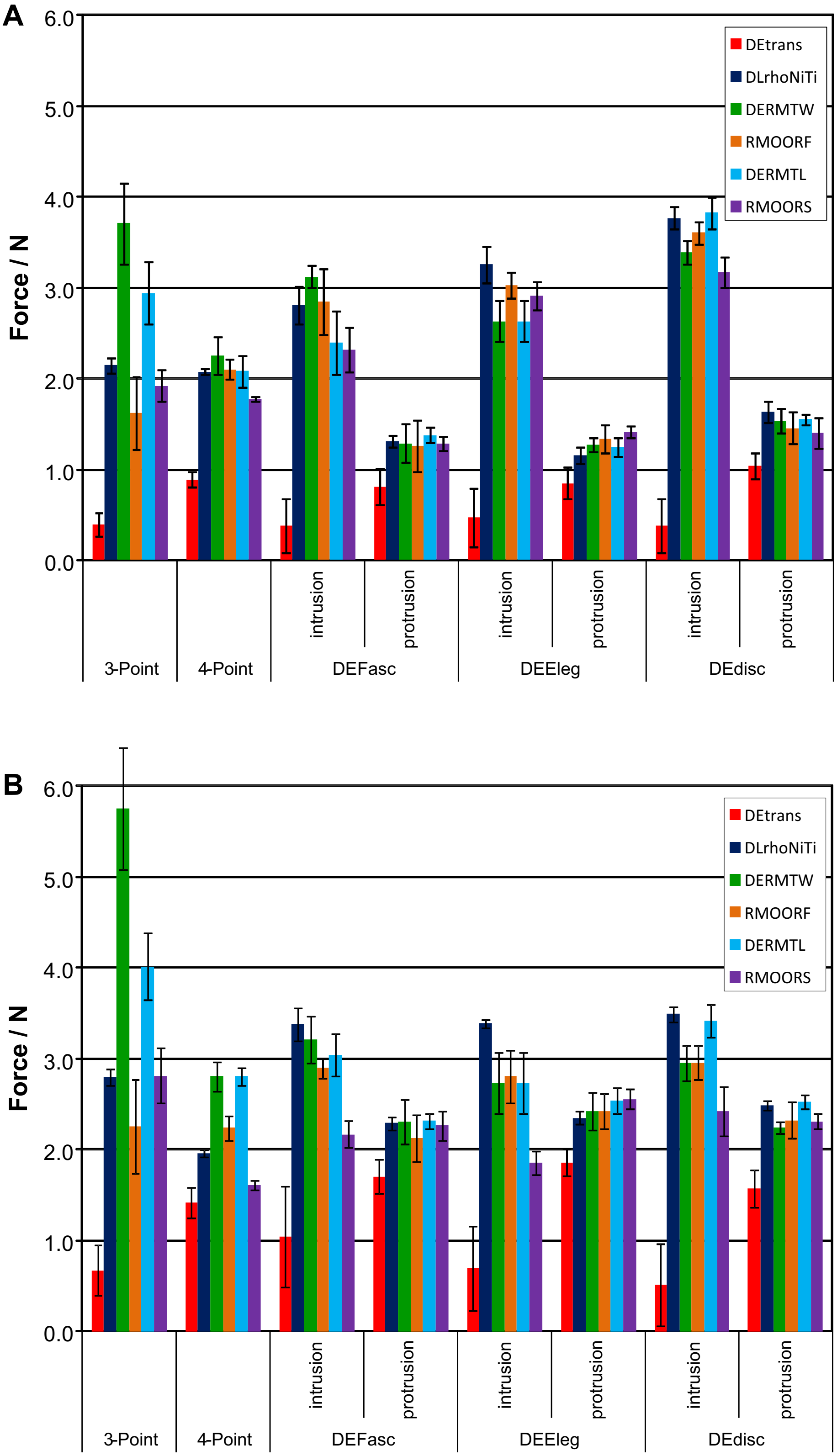


Fig. 6 Bar graphs of forces in three- and four-point bending and bending with different bracket arrangements at 1 mm (**a**) and 2 mm (**b**). Except for the translucent composite wire and the rematitan® wires in three-point bending, the forces are on a similar level. Minor differences exist, but do not seem to be clinically relevant

Abb. 6 Balkendiagramme der Kräfte im Drei- und Vierpunkt-Biegeversuch und bei Biegung im Bracketversuch bei Auslenkungen von 1 mm (**a**) und 2 mm (**b**). Außer für den transluzenten Kunststoffbogen und die rematitan®-Bögen im Dreipunkt-Biegeversuch waren die Kräfte auf vergleichbarem Niveau. Die geringfügigen Unterschiede erscheinen klinisch nicht relevant

For the bracket bending tests the deflection following the protrusion direction generated clearly lower forces than in the intrusion deflection. This is due to the fact that the elastics of the neighboring brackets are stretched by the deformed wire which reduced the force of the wire.

All differences in forces between three-point and four-point bending and bracket tests in intrusion direction were significant, except for the combination of the Fli® wire with the Elegance® bracket. Same holds for the comparison of the bracket tests in protrusion direction with three-point and four-point bending, where all differences were significant, except for the Fli® wire with elegance and Fascination® brackets. However, the significance of the differences between the various bracket/wire combinations showed an inconsistent pattern.

Totaling, forces were quite high, with maximum values up to 4.0 N (intrusion direction, Discovery® bracket, Dentalline, rhodinized NiTi and rematitan® Lite). Basically the results for the deflection of 2 mm (Fig. 5b) are similar, with slightly increased forces, due to the higher deflection. However, except for the composite wire, the increase was not linear, due to the superelastic behavior of all NiTi wires. At 2 mm, deflection forces in the protrusion direction almost reached the level of forces in the intrusion direction, as the elastic used for ligation reached its elastic limit.

Discussion

Nowadays a larger number of so-called esthetic wires are offered by manufacturers, including wires with different coatings and even fiber-reinforced composite wires. These wires have to be tested with respect to their biocompatibility as well as mechanical and biomechanical characteristics, especially regarding the forces generated during clinical application, in order to give the orthodontist guidelines for proper wire selection. Bending tests are recommended to best mimic the clinical situation.

The wire size used in this experiment was 0.018″ because the translucent wires are available only in 0.018″ size so matching sizes in the regular NiTi was used for comparison. Also, this size was used because some clinicians use 0.018″ wire as the initial wires and it is mainly used by many clinicians at the end of the levelling stage and before further stages of orthodontic treatment may be contemplated. Using smaller size wires may not represent differences in bracket geometry due to the large play between the wire and bracket slots.

Although the test does not perfectly simulate the clinical situation, most studies reported in literature used the three-point bending test to determine wire forces upon deflection [6, 7, 14, 15, 18, 24]. The ISO standard DIN EN ISO 15841:2007 [10] defines a test arrangement to give manufacturers guidelines how to report wire properties to the user (the orthodontist) based on standardized test procedures. The standard claims that forces have to be registered and reported at deflections of 3.0, 2.0, 1.0, and 0.5 mm on the unloading branch of a NiTi wire. Unfortunately, most translucent wires fractured at deflections around 2 mm and we did not have reliable force data for 3 mm deflection. Moreover, fluctuations at 0.5 mm deflection on the unloading branch were extreme, as most of the NiTi wires already left the unloading plateau or displayed a minor permanent (martensitic) deflection. Thus, we decided to exclude the force data at 0.5 and 3.0 mm and to compare the wires (1) when forces were on a clearly defined plateau (i.e., 1 and 2 mm deflection) and (2) forces at deflections where reliable values for all wires were available. This is a deviation from the standard but nevertheless presents sufficient data to compare the different products.

In 2006, Vestrynberg et al. [23] mentioned that a four-point bending test would be more appropriate when the elastic limit should be determined. According to Brantley et al. [8], the four-point bending test is more suitable to assess structural weakness. In our study, we did not see clinically relevant differences between three-point and four-point bending, except for the rematitan® wires, which will be discussed below. Sometimes the forces in four-point bending were even lower than in three-point bending (e.g., for the rhodinized NiTi and the Orthonol Superelastic®). Comparing the results in three- and four-point bending with the bracket test set-ups it can be stated that only minor, clinically nonsignificant differences were determined. As long as the free wire length is kept constant, the major influence for the force level is the wire type, i.e., in case of metallic materials the alloy the wire is made of or the type of composite used to produce a plastic wire. In so far, it is to be stated that the three-point bending test is a valuable method to compare forces of orthodontic wires in a highly idealized situation.

Force/deflection curves of superelastic NiTi wires display the forces on the loading and unloading branches. The activation, i.e., loading part of each curve, is the force needed to displace a wire and insert it into the bracket slot. The deactivation part of each curve, i.e., the unloading branch, is the force that acts on the brackets during treatment [7, 17, 21]. According to the ISO standard DIN EN ISO 15841:2007 [10], forces shall be measured at predefined deflections of 3, 2, 1, and 0.5 mm. In this study, we recorded the forces at 1 and 2 mm deflection, to ensure that the composite wire did not show fracture and could be compared to the other materials. Fracture of the glass-fiber-reinforced wires occurred at deflections exceeding 3 mm, sometimes even at lower deflections, indicating a risk of fracture in clinical application with larger tooth malpositions. Nevertheless, in all bending tests this wire type delivered the lowest forces within a clinical acceptable range.

The forces of the NiTi wires were quite high, with values ranging from 1.2 N (1 mm deflection in vestibular direction with the Fascination® bracket) to almost 6.0 N (2 mm in three-point bending with the rematitan® White). These findings demonstrate a variety of materials science facts that will be discussed in the following:

- The differences in forces in the intrusion and vestibular directions result from the elasticity of the elastomeric ligatures. Loading the wire–bracket–ligature complex in the vestibular direction results in a stretching of the ligatures of the two outer brackets. This results in a reduction of the force until the ligature is stretched to the elastic limit. From this point on, the force is dominated again by the elastic properties of the wires. Thus, the vestibular forces will approximate the vertical forces with higher deflections.
- Force levels are dominated by the wire and its mechanical characteristics in combination with the amount of deflection, although a minor influence results from variations in the test set-up. With this in mind, a wire dimension 0.46 mm may be regarded as inappropriate with tooth malpositions of around 1 mm and above. This even holds for NiTi wires of the tested type.
- Force levels of the NITI wires tested in this study are very similar, regardless of whether they were coated, uncoated, or surface modified. This finding is independent of the type of bending test used.
- The behavior of the coated and uncoated rematitan® wire (White and Lite) indicates the sensitivity of NiTi wires with respect to the manufacturing process. Figure 6 shows that rematitan® white (the green bar) and in part rematitan® Lite (light blue) display clearly higher forces in three-point bending. In all other tests, the forces were on a similar level as for the other wires. It is well-known that force levels of NiTi wires critically depend on the alloy composition, the manufacturing process, and the measurement temperature. As the temperature was kept constant at 37 °C for all measurements and the test geometry was identical for all specimens in the three test types (three- and four-point bending, biomechanical test), the high forces of the rematitan® wires in the three-point bending test can only result from material variations. The three-point bending test was performed first in the whole test series and new wires were taken for each test type. It seems that this resulted in the selection of 10 wire segments with high forces for the three-point bending test, as wires were taken from one package after the other. In all other tests, this wire had similar force levels as all the other NiTi wires.

Several other authors [2, 13] found significant reductions of forces with the surface modified or coated NiTi arch wires and argued that it is the reduced diameter of the NiTi core, surrounded by an epoxy resin. Our results cannot confirm these findings, as the forces of the coated wires compared to the uncoated wires are sometimes higher (e.g., 2.9 N versus 2.3 N for the FLI Wire Orthonol® against the Orthonol Superelastic® at 1 mm with the Elegance® bracket) and sometimes lower (e.g., 3.0 N for the rematitan® White and 3.4 N for the rematitan® Lite at 2 mm deflection with the Discovery® bracket). This is in accordance with the findings of Kaphoor and Sundareswaran [16] who found higher or lower forces or even no differences between coated and uncoated wires, depending on the manufacturer. This again is in contrast to the results reported by Elayyan et al. [12, 13]. Using a three-point bending test similar to that reported by Miura et al. [19], they found higher forces throughout for the same products studied by Kaphoor and Sundareswaran [16]. One may conclude that these in part inconsistent results may result from temperature variations, differences in test set-ups, or minor variations in the material compositions of the tested NiTi wire products.

The relatively high forces in the three-point bending compared to the four-point bending tests could be due to the fact that the total wire in the four-point bending test is longer (13.5 mm) than that in the three-point bending (10 mm). Figure 2 displays the typical deformation of the wire in the four-point bending test. Obviously, the wire is deformed in the central region and also in between the knuckles, thus, resulting in reduced stiffness compared to three-point bending. It could also be due to friction in the three-bracket model created by using elastic ligature. A further reason could be due to the fact that most measurements were performed in the deactivation part of the loading curve which might be the reason that the forces in the three-bracket model were not clearly higher than those for the three-point bending test as seen in all figures of the intrusion and protrusion loading/unloading curves.

Limitations of this study include the following: The three-bracket model using the elastics for wire fixation contains friction. This leads to a bias which may be of clinical significance; however, for standardization this has been done for all tested brackets and wires. Although the "play" between the tested wires and brackets might have an integral part of the study results, we expect this to be the same for all tested brackets since they are all of the same slot size. The possible elasticity of the mechanical component of the apparatus is of limited importance as it is rigid and the errors of measurement has already been tested [4]. The force values reported in this manuscript might reflect smaller deflections which is expected to be common clinical problem, we do not expect more deflection than the reported amount in this manuscript, and if there is an increased deflection, our results may not apply to this particular clinical situation.

Conclusions

The investigated coated NiTi wires generated similar forces as uncoated wires. Minor differences seem to result from variations of the material properties of the wires, due to the manufacturing process. The differences are not clinically relevant.

Translucent glass-fiber-reinforced composite wires generated significantly lower forces than the investigated NiTi wires with the same diameter and deflection. However, at deflections above 3 mm they have the risk to fracture.

Although the test set-up with brackets simulates the clinical bending situation best, the three-point bending test is an appropriate approximation to compare properties of orthodontic wires in bending. The results from the four-point bending test do not differ significantly although it is a still better approximation.

The combination of metal bracket and translucent wire generated the lowest forces.

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Compliance with ethical guidelines The accompanying manuscript does not include studies on humans or animals.

Conflict of interest A. Alobeid, C. Dirk, S. Reimann, T. El-Bialy, A. Jäger, and C. Bourauel state that there are no competing interests.

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