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DO ESTHETICS CONTRADICT WITH FUNCTION? IN VITRO ASSESSMENT OF LOAD DEFLECTION AND FRICTIONAL RESISTANCE OF COATED VERSUS UNCOATED SUPERELASTIC NICKEL-TITANIUM ARCHWIRES

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ABSTRACT

Objectives: The present study aimed to investigate the effect of esthetic coating on the load deflection properties, surface roughness and frictional resistance of superelastic Ni-Ti orthodontic wires.

Materials and Methods: Four types of Ni-Ti wires were investigated: Alpha Wire Super Elastic Ni-Ti, OrthoPro (Uncoated OP) and its coated counterpart: Alpha Wire Tooth-Coated Super Elastic Ni-Ti, OrthoPro (Coated OP); Super-elastic Nitanium, Ortho Organizer (Uncoated OO) and its coated counterpart: Super-elastic Nitanium Tooth Tone, Orthodontic Organizer (Coated OO). The load deflection properties were investigated using three-point elastic bending test by a universal testing machine (Lloyd Instrument LR5K series, London, UK) to record the average unloading force (n=8). The surface roughness was measured using a non-contact profilometer (ZYGO Maxim-GP 200, USA) (n=4). The static and dynamic frictional resistances were measured using a specially designed test assembly that allows sliding the wires through the slots of monocrystalline zirconia brackets using a universal testing machine (n=8).

Results: No significant difference was found between the coated OP wires and their uncoated controls regarding the load deflection, surface roughness or frictional resistance whether static or dynamic. On the contrary, compared to their uncoated group, the coated OO wires showed significantly lower average unloading force, higher surface roughness, and higher static and dynamic friction.

Conclusions: The effects of the esthetic coating on the critical function-related properties of orthodontic wires vary from one manufacturer to another which indicates that satisfying the esthetic demand does not always come at the expense of wire function.

KEYWORDS: Esthetic, coated, superelastic, Nickel-Titanium, load-deflection, surface roughness, frictional resistance, static friction, dynamic friction

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INTRODUCTION

During the orthodontic treatment, tooth movement is attained by applying orthodontic force that is delivered through a system which comprises both orthodontic bracket and archwire. Since they were introduced in the late 1970s, the Ni-Ti wires gained worldwide acceptance in the orthodontic practice due to their unique superelastic properties [(1)]. In the past, the functional demands were the main consideration during orthodontic treatment. However, with the increasing number of adult patients seeking orthodontic treatment, esthetics became a prime concern [(2)]. The introduction of ceramic brackets partially solved the problem, yet, the metallic color of the orthodontic wires remained an issue until tooth-colored archwires, whether epoxy- or Teflon-coated, became commercially available [(3)]. Although considering esthetics during orthodontic treatment is critical for achieving patient satisfaction, these considerations should not, by any means, come at the expense of the functional requirements. Otherwise, the course of the orthodontic treatment may be compromised or delayed in such a way that neither the patient nor the orthodontist would be satisfied.

Controversial data are available in literature regarding the effect of the esthetic coating on the properties of orthodontic wires [(2)]. The two main biomechanical strategies used to achieve orthodontic tooth movement are: frictionless and frictional (sliding) mechanics [(4)]. The wire's load deflection characteristics and frictional resistance are two essential wire properties that influence the rate of tooth movement when frictionless or sliding mechanics are used respectively [(4,5)].

The unloading force values recorded while testing the wire's load deflection properties represent the amount of force that can be delivered by the wire and hence, that would generate tooth movement [(5)]. Needless to say, this force should be within the ideal force range that would allow effective tooth movement without compromising the integrity of the supporting periodontal structures [(6)]. While several studies reported that the esthetic wire coating decreased the amount of force delivered to the teeth by the Ni-Ti wires [(5,7)], other researchers found that the coated wires delivered comparable forces to that delivered by uncoated wires of the same size [(8,9)]. On the other hand, some studies revealed that only at small deflection distances (1 mm) does the coating influence the delivered force, while no significant effect could be detected at larger deflections (2 and 3 mm) [(3,10)]. It should be noted that the results of some of these studies cannot be used to specifically answer the question of whether the coatings could affect the force delivery or not. This is because some authors compared coated and uncoated Ni-Ti wires having the same size but produced by different manufacturers [(9)].

Friction between the wire and the slot of the orthodontic bracket is another critical factor that greatly influences the clinical performance of the orthodontic wire when sliding mechanics are used, such as during space closure [(4)]. Friction is defined as the force that opposes a relative movement when an object moves tangentially against another. It was estimated that about 60% of the generated orthodontic force is consumed in overcoming the frictional resistance between the wire and the bracket [(11)]. Distinction should be made between two types of friction; static and dynamic (kinetic). The static friction is the force needed to start the relative movement between the wire and bracket while the dynamic friction is the force needed to maintain such movement after it has already started [(11)]. During space closure, the tooth does not follow a straight sliding path along the archwire. Instead, it slides along the archwire through many cycles of alternating small increment tipping and uprighting movements [(12)]. Therefore, orthodontic space closure is influenced by both static and dynamic friction [(13)]. It has already been established that the wire surface roughness is an important variable that is positively correlated to the wire-bracket friction [14]. The effect of the esthetic wire coating on the wire's frictional resistance has been a controversial issue so far. Although some researchers found that the polymer coating of the Ni-Ti wires lowered their friction coefficients [15], conflicting findings were reported by other authors who found that the frictional forces of the coated wires were equal to or greater than those of the uncoated ones [13].

From the foregoing review, it is evident that there is still a knowledge gap regarding the effect of the wire coating on its function-related properties. This gap needs to be filled by further research. Thus, the aim of the current study was to investigate the effect of the epoxy esthetic coating of the Ni-Ti wires on their load deflection, surface roughness and frictional resistance with ceramic brackets.

The tested null hypotheses were: (1) the epoxy esthetic coating of the Ni-Ti wire does not affect the wire's load-deflection characteristics, and (2) the epoxy esthetic coating of the Ni-Ti wire does not affect the surface roughness or wire-bracket friction.

MATERIALS AND METHODS

Materials

Superelastic preformed Ni-Ti wires supplied by two manufacturers, with round cross-sections and nominal sizes of 0.016 inch, were investigated. From each manufacturer, two types of wires were tested: uncoated (control) wires and epoxy-coated wires with the same nominal dimensions. The investigated wires are shown in Table (1).

Methods

Load-deflection characteristics

The three-point elastic bending test was used to assess the load deflection characteristics of the Ni-Ti wires as recommended by the ADA specification no.32 [16]. Straight 30mm-long wire segments were obtained by cutting the two posterior parts of the pre-formed arch-shaped wires. Eight wire segments from each group were tested (n=8). During the test, each wire segment was placed on a specially designed holding frame that provided a beam length of 14 mm. The wire was immersed in a 37^{o} C water bath one minute before as well as during the test to simulate the clinical conditions and to ensure the austenite-martensite phase transformation of the Ni-Ti wire. The water bath temperature was monitored using a thermocouple (ERO electronic, Italy) and maintained using a portable water heating coil. The assembly used for the load deflection test is shown in Fig.1. A metallic pole attached to the upper member of a universal testing machine (Lloyd Instrument LR5K series, London, UK) was used to deflect the wire at its midpoint to a distance of 3 mm at a crosshead speed of 1 mm/min [3,16]. Using the same crosshead speed, the wire was then unloaded until a force value of zero was recorded. During the test, the deflection distances and their corresponding force values were recorded and

TABLE (1): The four wire groups investigated in the study

Manufacturer	Wire commercial name	Group name	Type of coating	Nominal wire size (in inches)	Product code
Ortho Pro Dent, USA	Alpha Wire Super Elastic Ni-Ti	Uncoated OP (Control)	--------	0.016	601-07
	Alpha Wire Tooth-Coated Super Elastic Ni-Ti	Coated OP	Epoxy coating	0.016	601-07TC
Ortho Organizers, USA	Super-elastic Nitanium Archwire	Uncoated OO (Control)	--------	0.016	100-654
	Super-elastic Nitanium Tooth Tone archwire	Coated OO	Epoxy coating	0.016	100-884

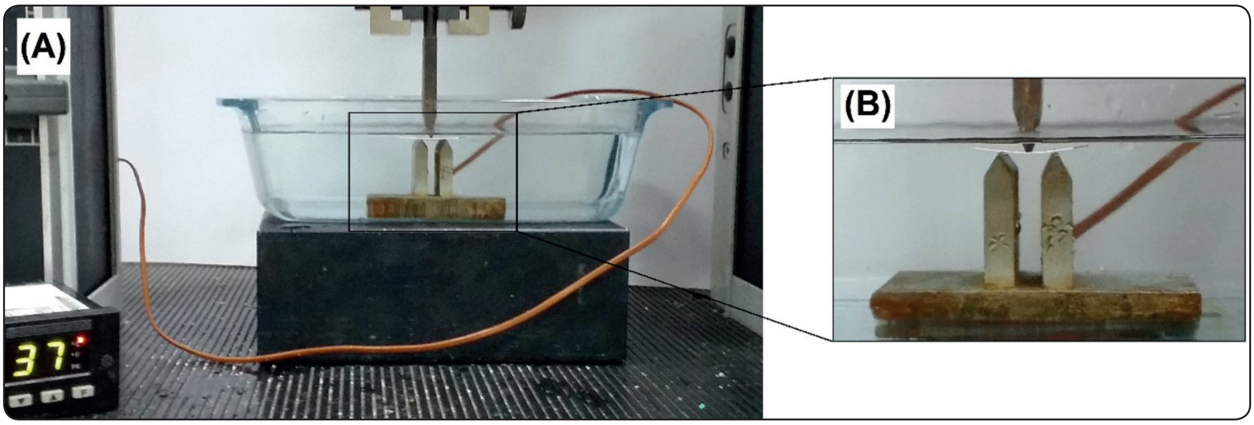

Fig. (1): (A) The three-point elastic bending test assembly, (B) The wire supported by the holding frame and deflected at its midpoint

plotted to generate a load-deflection curve for each Ni-Ti wire (Fig.2). The obtained curve showed the characteristic loading and unloading plateaus of the superelastic Ni-Ti wires. The unloading plateau of the load deflection curve was considered the relevant part to the current test since it represents the actual force values that the wire exerts on the tooth during orthodontic treatment and that actually generate tooth movement *in vivo*. The "average unloading force", the property that was used to represent the deflection behavior of each wire, was calculated as an average of all force values recorded between the deflection distances of 1 mm and 2.5 mm during unloading (Fig. 2).

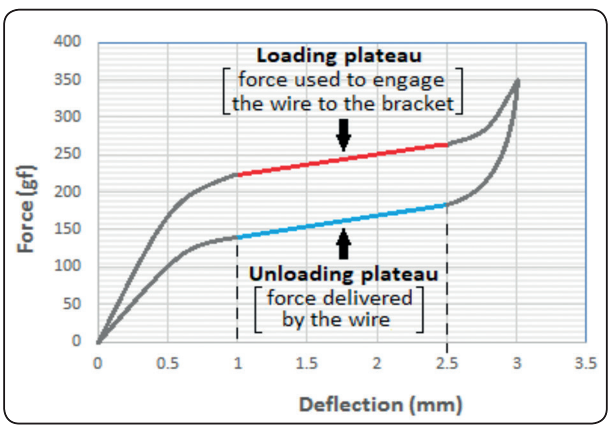

Fig. (2): Illustrative load-deflection curve of a Ni-Ti wire. The "average unloading force" was calculated as the average of all force values along the blue segment of the unloading plateau.

Surface roughness:

The arithmetic mean roughness (Ra) of the wires was measured with a vertical measurement accuracy of 0.01 µm using a non-contact profilometer (ZYGO Maxim-GP 200, Zygo Corporation, USA). For each group, four wire segments were tested (n=4) and for each segment, two profilometric scans were performed at two different sites and an arithmetic roughness value was determined for each scan. This gave rise to eight measurements for each group.

Frictional Resistance:

The frictional resistance between the wires and ceramic brackets was measured using a custom made test assembly, modified from that described by Mantel [17] (Fig.3). The assembly consisted mainly of two steel rods (4mm x 4mm x 8cm) attached to the upper and lower grips of a universal testing machine (Lloyd Instrument LR5K series, London, UK). On the rod attached to the upper member, three steel brackets were cemented, equally spaced on one straight line using Single Bond Universal adhesive (3M, ESPE, USA) that was cured for 40 seconds using a LED light polymerizing unit (Blue phase II, Ivoclar Vivadent, Schaan, Liechtenstein, Austria). A forth ceramic bracket was cemented on the lower rod so that when both rods were attached to the machine's grips, the four brackets would be aligned on the same straight line (Fig. 3). It should be noted that the role of the three steel brackets was only to hold the wire firmly from one end while its other end was being pulled though the ceramic bracket. Before starting the test, it was essential to ensure that the wire to be tested was passing passively in the slot of the ceramic bracket i.e. without mechanical hindrance. Thus, the wire was ligated to the three holding metallic brackets on the upper rod using O-ties ligatures (Ortho Pro chain elastics, USA) while the wire's lower part was allowed to pass freely in the slot of the ceramic bracket without ligation. The universal testing machine was operated to pull the wire through the ceramic bracket slot (non-ligated) for a distance of 1 mm. The wire was considered to be passively positioned within the bracket slot if the force needed to pull it through the slot was less than 2 gf. If the recorded force exceeded 2 gf, the lower rod was unlocked from the lower testing machine grip and its position was adjusted then the passive positioning was retested until a passive set up was ensured. Before starting the test, the distance between the two rods was adjusted to be 1 mm and the wire was ligated to the ceramic bracket using an O-tie ligature. In order to simulate the clinical conditions, the elastomeric ligatures were immersed in distilled water for 24 hours before the test to allow time for imbibition similar to that occurring intraorally and were removed from the water immediately before testing. Also, a drop of distilled water was injected on the ceramic bracket slot just before testing to provide lubrication analogous to that taking place *in vivo*. The universal testing machine was then used to pull the wire at a crosshead speed of 1 mm/min for a distance of 5 mm and the force values were recorded throughout the testing distance. The highest force that was needed to start a relative movement between the wire and the ceramic bracket was designated as "static friction". The "dynamic friction" was calculated as the average of nine force values recorded at interval distances of 0.5 mm throughout the 5 mm testing distance. The frictional resistance test was performed on eight wires for each wire group (n=8).

Statistical analysis

The data were presented as means and standard deviation values. Data were explored for normality using Kolmogorov-Smirnov and Shapiro-Wilk tests and showed parametric (normal) distribution. Independent sample-t test was used to compare between independent samples for parameric data. The significance level was set at $P \leq 0.05$. Statistical analysis was performed with IBM® SPSS® Statistics Version 20 for Windows.

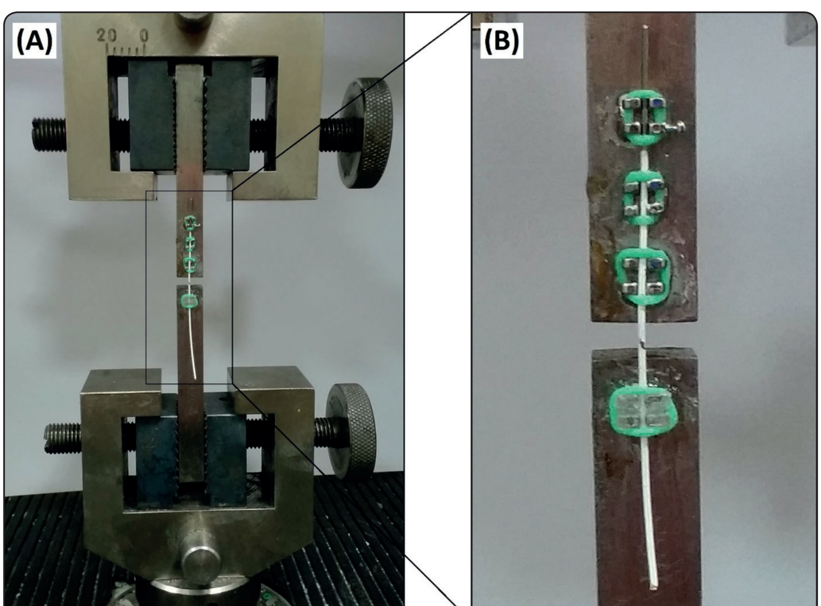

Fig. (3): (A) The frictional resistance test assembly, (B) The wire ligated to the three fixation steel bracket (on the upper rod) and the test ceramic bracket (on the lower rod).

RESULTS

Load deflection:

The OP wires, whether coated or uncoated, exhibited significantly higher average unloading force compared to the corresponding OO wires (p<0.001 and p=0.001 respectively). No statistically significant difference in load deflection was found between uncoated and coated OP wires (p=0.361). On the other hand, the coated OO wires showed significantly lower average unloading force compared to their uncoated controls (p<0.001) (Table 2 and Fig. 4). An overlay of four load-deflection curves of four wires representing the four groups is shown in Fig.5.

TABLE (2): Mean, standard deviation values and the statistical results of the average unloading force (gf):

Variables	OP wire	OO wire	P-value
	Mean ± SD	Mean ± SD	
Uncoated	217.61 ± 16.01	188.35 ± 7.12	0.001*
Coated	206.92 ± 25.11	121.11 ± 10.05	<0.001*
P-value	0.361	<0.001*	

: Significant (p<0.05)

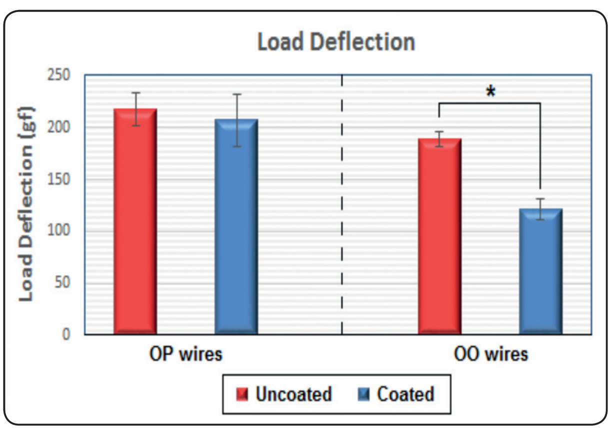

Fig. (4): The average unloading force (gf) of the uncoated and coated OP and OO wires [*: Significant difference].

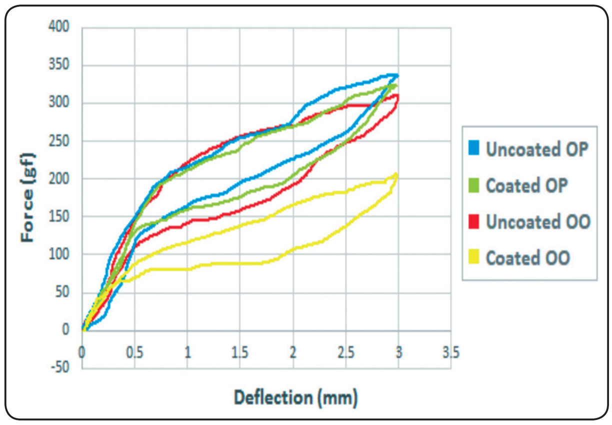

Fig. (5): Overlay plot of the load-deflection curves of four wires representing the four groups

Surface roughness:

There was no statistically significant difference in the arithmetical mean roughness (Ra) between the coated and uncoated OP wires (p=0.113). In contrast, the coated OO wires exhibited significantly higher arithmetical mean roughness compared to their uncoated controls (p<0.001) (Table 3 and Fig.6).

TABLE (3): Means, standard deviation values and the statistical results of the arithmetical mean roughness (Ra) (μm):

Variables	OP wire	OO wire	P-value
	Mean ± SD	Mean ± SD	
Uncoated	0.06 ± 0.02	0.04 ± 0.02	0.267
Coated	0.05 ± 0.02	0.49 ± 0.15	<0.001*
P-value	0.113	<0.001*	

: significant (p<0.05)

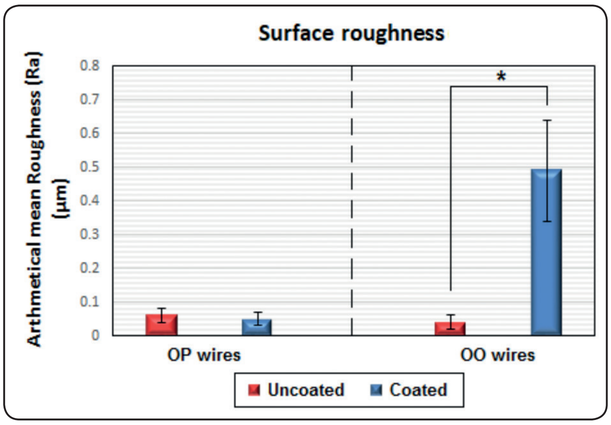

Fig. (6): The arithmetical mean roughness (μm) of the uncoated and coated OP and OO wires [*: Significant difference].

Frictional resistance:

Static friction:

No statistically significant difference was found in the static friction between the coated and uncoated OP wires (p=0.125). On the other hand, the coated OO wires showed a significantly higher static friction compared to their uncoated counterparts (p<0.001) (Table 4 and Fig.7).

TABLE (4): Means, standard deviation values and statistical results of the static friction (gf):

Variables	OP wire	OO wire	P-value
	Mean ± SD	Mean ± SD	
Uncoated	99.10 ± 31.46	43.22 ± 15.15	0.001*
Coated	128.55 ± 32.92	101.98 ± 10.41	0.065
P-value	0.125	<0.001*	

****: significant (p<0.05)***

Dynamic friction

Regarding the OP wires, no statistically significant difference was found between the coated and uncoated groups (p=0.782). In contrast, the coated OO group showed significantly higher dynamic friction than the uncoated group (p=0.013) (Table 5 and Fig.7).

TABLE (5): Means, standard deviation values and statistical results of the dynamic friction (gf):

Variables	OP wire	OO wire	P-value
	Mean ± SD	Mean ± SD	
Uncoated	91.62 ± 27.92	42.81 ± 13.04	0.001*
Coated	95.65 ± 25.19	70.97 ± 22.01	0.075
P-value	0.782	0.013*	

****: significant (p<0.05)***

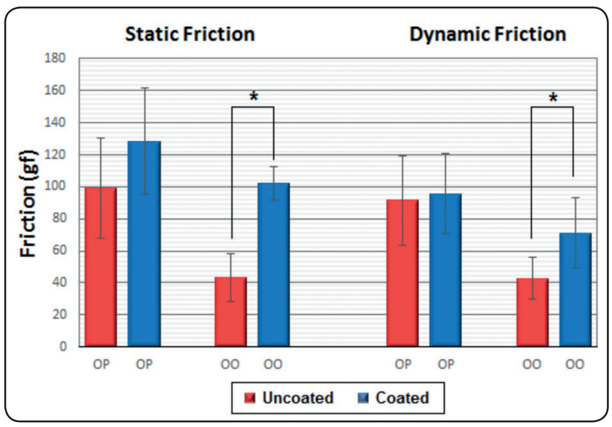

Fig. (7): The static and dynamic friction (gf) of the uncoated and coated OP and OO wires [*: Significant difference].

DISCUSSION

Although esthetically-coated wires have relatively satisfied the patients' eagerness for esthetics, concerns have raised that these coating may adversely affect the wire's function. Both load deflection and frictional resistance are essential properties that influence the clinical performance of orthodontic wires when used in frictionless (non-sliding) or sliding mechanics respectively.

In the current study, the three-point elastic bending test was used to investigate the load deflection properties of the Ni-Ti wires. The load-deflection curves of all investigated wires exhibited the typical loading and unloading plateaus which confirms their superelastic behavior. It must be noted that the upper loading plateau of the diagram is of no interest in the current research as it only denotes the force needed to engage the wire to the bracket (Fig.2). The important part of the curve is its lower unloading plateau since it represents the force that the wire delivers to the tooth during the orthodontic treatment course [7].

The results showed that the unloading force of the uncoated OP wires was significantly higher than that of the uncoated OO wires although both wires had the same dimensions. This may attributed to the fact that the load deflection properties of the Ni-Ti wires are influenced by several factors other than just the wire size [18]. Examples of these factors include the heat treatment that the Ni-Ti alloy receives during fabrication, the grain size as well as the relative proportions of the metallurgical phases, i.e. the austenite/martensite ratio, that persist after the manufacturing process [19].

To evaluate the effect of the esthetic coating on the load deflection, the unloading forces of both uncoated and coated wires of each manufacturer were compared. No significant difference was found in the force delivered by both coated and uncoated OP wires of the same nominal size. These results are in agreement with those reported by Pop et al [5] and Aghali et al [7]. In contrast, the coated OO wires showed significantly lower unloading force compared to the uncoated control wires of equal nominal size which comes in accordance with the results reported by Murayama et al [8]. Based on these results, the first null hypothesis was rejected. This difference in the effect of coating between the two different wire brands can be explained if we put into consideration the fact that every coated wire consists of an inner metallic core covered by a thin layer of the esthetic coating (Fig.8). Some manufacturers report the nominal sizes of their coated wires as the diameter of the inner core metallic wire without putting in account the thickness of the polymer coating. They only mention the coating thickness as auxiliary data. On the other hand, other manufacturers report their wires' size as the external diameter of the coated wire i.e. the coating thickness is included in the overall reported nominal wire diameter [20]. This means that the orthodontist may end up having two wires from two different manufacturers both having the same nominal size although their inner metallic cores have actually two different diameters (Fig.8). This may explain why the coating of one type of the wires investigated in the current study decreased its unloading force while the coating of the other wire type did not. To validate this explanation, the esthetic coatings of the two investigated coated wire types were gently peeled off and the diameter of the inner metallic core wires were measured using a precision micrometer (Mitutoyo digimatic micrometer, Japan). The diameters of the uncoated wires were also measured. It was found that the peeled OP wire had the same diameter as the uncoated OP wire which explains why both wires showed no significant difference in their unloading force. In contrast, the peeled OO wire had a smaller diameter (0.002 inch less) than its uncoated counterpart which is consistent with the fact that the coated OO wire delivered significantly lower force compared to its uncoated control. Based on these results, the difference among manufacturers regarding the way of reporting the wire size should be taken into consideration by the orthodontists when selecting the correct wire size for each clinical situation.

Unfortunately, no enough evidence-based research is currently available to specify the exact magnitude of the optimum orthodontic force that would provide maximum cellular response without jeopardizing the vitality of the tooth-supporting tissues [21]. However, an estimated force range of 50-300 gf was considered acceptable by some studies [6].

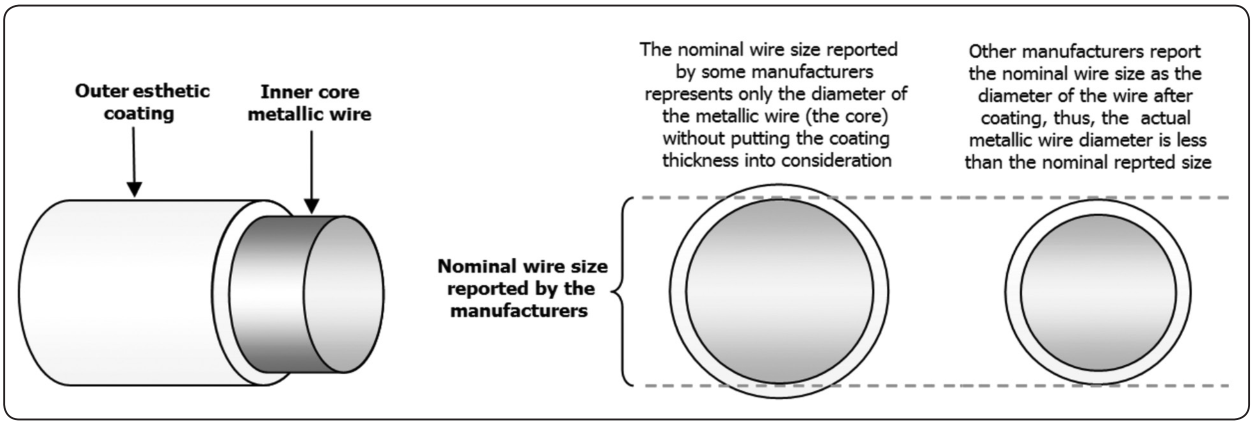

Fig. (8): Structure of the esthetically-coated wires and the different methods adopted by manufacturers to report the nominal wire size

Accordingly, the forces delivered by all wires tested in the current study, including even the coated OO wires which had the significantly lowest unloading force, were still within the acceptable orthodontic force range reported in literature.

Based on the results of the roughness and frictional resistance, the second null hypothesis was also rejected. Regarding the surface roughness, no difference was found between both uncoated and coated OP wires which indicates that the coating did not adversely affect the wire roughness. These findings agree with the results reported by Rudge et al [22]. On the contrary, the coated OO wires exhibited significantly higher surface roughness (almost a tenfold increase) compared to the uncoated OO controls. These findings are contradictory to those published by Bravo et al who reported that the epoxy coatings decreased the Ni-Ti wires surface roughness [15]. This difference in results may be attributed to the fact that the authors of the former study experimentally coated the Ni-Ti wires with epoxy using a dipping process and compared the roughness with the uncoated wires. Thus, their results would not in fact reflect the actual roughness of the commercially available coated wires which are coated through a totally different process that is called electrostatic coating.

The electrostatic coating process, or E-coating, involves multiple steps including: (1) creating a high-voltage electrostatic field between the wire and the epoxy using opposite electrical charges, (2) air-spraying atomized liquid epoxy particles on the wire, and finally (3) baking the coated wire in a chamber furnace to allow the adhering epoxy particles to melt and flow together to form a continuous protective film [23]. It is worth mentioning that this coating procedure is sometimes preceded by a roughening process for the wire surface in order to provide secure mechanical interlocking between the wire surface and the coating. It has been reported that different factors related to this particular coating process, like the applied voltage, the powder air spraying pressure and time and the wire's surface pretreatment, can influence the quality of the coating in terms of its thickness, roughness and surface charge [24]. Thus, it is possible that the variations in the coating parameters used by the different manufacturers may account for the disparity in the effect of the wire coating on the surface roughness of the different wire brands investigated in the current study.

Comparable results were obtained for both static and dynamic friction where no significant difference was found between the coated and uncoated OP wires while the coated OO wires showed significantly higher static and dynamic friction compared to their uncoated controls. These results concur with the results of the surface roughness which may suggest that the difference in the effect of coating on the friction of the two wire brands may be related to the difference in their surface roughness after coating. It must be highlighted that although the coating significantly increased the friction of the OO wires compared to their uncoated controls, the friction of these coated OO wires did not differ significantly from the coated OP wires. This is probably due to the fact that the uncoated OO wires originally had much lower (less than half) static and dynamic friction compared to the uncoated OP (Tables 4 and 5).

The friction results of the current study are in agreement with those reported by Rudge et al who found that the esthetic coating may or may not affect the Ni-Ti wire's friction [22]. However, converse results were reported by Nance who found that the friction of the epoxy-coated Ni-Ti archwires was lower than that of the non-coated ones [25]. This difference in results may be ascribed to the difference in the experimental parameters where the latter study tested the friction under dry condition unlike our present study which used wet conditions. Being of polymeric nature, both the epoxy coating as well as the polymeric ligatures, used to engage the wire to the bracket, may imbibe water under wet conditions thus undergo some degree of swelling which may increase the frictional force compared to the friction that occurs during dry testing.

CONCLUSIONS

Within the limits of the current study, the following conclusions could be drawn:

1. The epoxy esthetic coating decreases the average unloading force of some wire brands but it does not affect the unloading force of others.
2. The effect of the wire coating thickness on the actual wire diameter should be taken into consideration during wire selection because the way of reporting the nominal wire size differ from one manufacturer to another.
3. The epoxy esthetic coating of some wire brands increases the surface roughness and frictional resistance with ceramic brackets while other wire brands are not affected by these coating.
4. The use of esthetically-coated wires to satisfy the esthetic demand does not always compromise the wire's function.

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