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Effect of zirconium oxide nano-coating on frictional resistance of orthodontic wires

Amin Golshah and Shirin Asadian Feyli

Abstract

Objectives: Minimizing the frictional force between orthodontic wire and brackets is imperative to safely obtain a more favorable result by applying lower loads. Several methods have been proposed for this purpose such as changing the wire shape/size, changing the bracket design, and coating wires with different materials. This study aimed to assess the effect of zirconium oxide ($ZrO2$) nano-coating on frictional resistance of three types of orthodontic wires.

Materials and Methods: This *in vitro*, experimental study evaluated 42 pieces of nickel-titanium (NiTi), stainless steel (SS), and beta-titanium (TMA) orthodontic wires, and 42 maxillary canine brackets. The samples were divided into six groups with and without ZrO2 nano-coating. The nano-coating was applied on the wires using the sol-gel technique. The presence of ZrO2 nano-coating was evaluated by scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDX). The surface roughness of the samples was evaluated using atomic force microscopy (AFM). The brackets and wire had a 5° angle relative to each other. The static and kinetic friction of the samples were evaluated in the presence of artificial saliva and occlusogingival movements in a universal testing machine. Data were analyzed by the Shapiro–Wilk's test, one-way ANOVA, Kruskal–Walli's test, Mann–Whitney U test, independent t-test, and Tukey's test.

Results: ZrO2 nano-coating was only observed on TMA wires. The surface roughness of coated NiTi and SS wires had no significant difference from that of non-coated wires ($P > 0.05$). However, this difference was significant for TMA wires with and without the coating ($P < 0.05$). The static and kinetic friction were not significantly different between wires with and without coating ($P > 0.05$).

Conclusions: ZrO2 nano-coating could only be applied on TMA wires, and had no significant efficacy for reduction of static or kinetic friction of TMA wires.

Keywords:

Frictional force, nano material, orthodontic treatment, zirconium oxide nanoparticles

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Introduction

In fixed orthodontic treatment, the wire should be able to slide through the bracket slots to cause tooth movement. However, frictional resistance is a barrier to this process.[1] Evidence shows that approximately 50% of the force required for tooth movement is used to overcome friction.[2] Thus, to achieve the desired tooth movement, excessive orthodontic forces should be applied to wires,[3] which can lead to anchorage loss and increase the risk of root resorption,[4] and eventually prolong the course of treatment.[5] It is assumed that decreased frictional resistance can enhance leveling and alignment of teeth and space closure, and consequently shorten the treatment course. Therefore, reduction of friction forces during orthodontic treatment can significantly increase the success of treatment.[6] Friction depends on three factors, namely molecular adhesion (electromagnetic forces between atoms), interlocking caused by surface

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roughness, and the plowing effect.[7,8] In orthodontics, several factors affect the frictional resistance such as the composition of wire and bracket,[9] surface properties of wire and bracket,[10] bracket slot angle,[11] type of bracket and its width,[12] size of wire,[13] composition of ligature, and ligation force.[2,14] Additionally, saliva, dental plaque, and corrosion are among the biological factors affecting bracket-wire friction.[14]

To date, several methods have been proposed to overcome the bracket-wire friction such as changing the shape and size of wires, changing the bracket design, and coating the wires with different materials.[4] Nanotechnology is an evolving field of science dealing with materials in nanoscale dimensions. Nanotechnology has gained increasing popularity in the synthesis of dental materials with enhanced properties.[15] Wire coating with nanoparticles is recommended when an angle forms between the wire and bracket because, in presence of high frictional resistance, nanoparticles are released and serve as a solid lubricant on the surface and decrease the frictional forces.[16] Moreover, the presence of a contact angle between the wire and bracket during orthodontic tooth movement plays a role in friction.[6] Zirconium oxide (ZrO2) nanoparticles have several favorable properties such as high resistance to oxidation, high thermal and mechanical resistance, high resistance to corrosion,[17] and optimal biocompatibility.[18,19]

The use of zirconium alloy or zirconium coated with ZrO2 for orthopedic implants is gaining increasing popularity in medicine since it decreases friction and confers wear resistance, especially to artificial joints.[20] ZrO2 coating [Zirconium Nitrate (Zr (NO3)4)] is used in cardiovascular, vascular, and cutaneous implants, catheters, and other surgical instruments. This coating increases insulin compatibility, blood compatibility, corrosion resistance, durability, and electrical isolation, and decreases thrombogenesis and friction.[21] This coating is also applied on guide wires.[22] However, ZrO2 coating has not been applied on orthodontic wires. Therefore, this study aimed to apply ZrO2 nano-coating on different orthodontic wires to assess its efficacy in the reduction of friction.

Methods

This *in vitro*, experimental study evaluated 42 pieces of straight wires with rectangular and round cross-sections from three different types, namely 0.016-in nickel-titanium (NiTi; Ortho Technology, USA), 0.017 x 0.025-in beta-titanium (TMA; Ortho Technology, USA), and 0.017 x 0.025-in stainless steel wires (SS; Technology Ortho, Washington, USA). The sample size was calculated to be 7 in each group (a total of 42) assuming alpha = 95, power of 90%, accuracy = 0.02, and standard deviation of frictional force to be 0.012 and 13 for the two groups with and without coating, respectively.[23]

The wires were divided into six groups; out of which, three groups received ZrO2 coating. The study groups (n = 7) were as follows:

Group 1. NiTi wires coated with ZrO2.

Group 2. SS wires coated with ZrO2.

Group 3. TMA wires coated with ZrO2.

Group 4. NiTi wires without coating.

Group 5. SS wires without coating.

Group 6. TMA wires without coating.

Moreover, 42 maxillary canine brackets (0.022; Discovery®, Dentaurum, Germany) were used, and the wires were passed through the slots. The ZrO2 nano-coating was applied on the surface of the three types of orthodontic wires.[7]

Application of nano-ZrO2 coating on orthodontic wires as a solid lubricant

ZrO2 nano-coating was produced using the sol-gel hydrolysis technique. The zirconium (IV) propoxide solution (0% wt. Fluka in propanol) was used as a metal oxide precursor. The preparation of the starting sol was carried out in a dry Erlenmeyer flask because of the high reactivity of zirconium (IV) propoxide in the presence of moisture. Before deposition, the wires were rinsed with water and acetone and dried at 80°C.

To apply thin films, the surface of the wires was coated with nano-structured ZrO2 using the sol-gel technique. At first, the ZrO2 solution precursor was stabilized at room temperature by dissolving zirconium (IV) propoxide (1 mL) in a propanol solvent (30 mL) and stirring for 30 min. Next, a burette was used to gradually add a mixture of 1 mL water and 10 mL propanol to the aforementioned solution while stirring. The required sol was obtained as such. The orthodontic wires were coated using the dip-coating method. The gel obtained from the sol was allowed 24 h to dry at room temperature. After washing the wires, a thin transparent film of ZrO2 was obtained.

Next, the surface roughness of the coated and non-coated wires, and the surface topography and morphological changes of the coated wires were evaluated using AFM; Ara Research, Tehran, Iran). Field emission scanning electron microscopy (FESEM) was also used to obtain photographs of the surface of the coated samples. The presence of Zr element on the surface of the wires was evaluated using energy-dispersive X-ray spectroscopy (EDX).

Next, a custom-made device (99294, Iran patent) was designed for the lower compartment of the universal testing machine (STM 20, Santam, Tehran, Iran). This device could simulate occlusogingival tooth movements by applying 12 v voltage by a transformer to an aluminum plate attached to the fixture-holding plate, causing its movement [Figure 1a]. The brackets were fixed to the fixture while the fixture was perpendicular to the fixture-holding plate. The fixture was free to rotate. Thus, the bracket could be positioned over it with different angulations [Figure 1b]. In addition to the simulation of the occlusogingival tooth movements, the device could simulate the oral environment by using artificial saliva, which was poured into its cylindrical container. To do so, the bracket was placed at the center of the fixture and fixed with cyanoacrylate glue at a 5° angle.[23] Next, the orthodontic wire was ligated to the bracket wings with an elastomeric O-ring (Ortho Technology, USA). A 150 g weight was attached to the lower end of the wire[16,23,24] and placed in the container containing artificial saliva. The upper end of the wire was attached to the tension load cell of the universal testing machine [Figure 1c]. The machine was adjusted to pull the wire through the bracket slot by 5 mm at a crosshead speed of 10 mm/min. The maximum load to overcome static friction was determined according to the force/displacement curve drawn by the universal testing machine,[9,25] and the mean frictional force along the displacement was considered as the kinetic friction. The brackets and wires were replaced after each sliding to provide similar standardized conditions for all samples.

Data were analyzed using SPSS version 25 (SPSS Inc., IL, USA) at a 0.05 level of significance. The normal distribution of data was evaluated by the Shapiro–Wilk's test. Independent t-test, one-way ANOVA, and Tukey's test were applied to analyze the normally distributed data; while the Kruskal–Wallis and Mann–Whitney U tests were applied to analyze data with non-normal distribution.

Results

Surface roughness

Figure 2 shows the AFM topography images of the surface roughness of wires with and without ZrO_2 nano-coating measuring 5 x 5 µm. Figure 3 shows the same topography images three-dimensionally.

Table 1 presents the surface roughness (Ra) of the samples in the six groups. The minimum and maximum surface roughness values were noted in coated SS wires and non-coated NiTi wires, respectively. According to the Shapiro–Wilk's test, the surface roughness data were not normally distributed ($P < 0.05$). Thus, the Kruskal–Walli's test was applied for multiple comparisons, and the Mann–Whitney U test was used for pairwise comparisons. The surface roughness of the coated wires was first compared. Then, the surface roughness of the non-coated wires was compared. Finally, the surface roughness of the coated and non-coated wires was compared with each other. No significant difference was noted in comparison of the surface roughness of coated ($P > 0.05$) and non-coated ($P > 0.05$) wires with each other. The comparison of the coated and non-coated wires independently for each wire type revealed a significant difference only in the surface roughness of coated and non-coated TMA wires ($P < 0.05$).

FESEM and EDX

As shown in Figure 4, the EDX analysis revealed that among the coated wires, only the coated TMA wires had considerable amounts of Zr.

Table 1: Surface roughness (Ra) of samples in the six groups

Group	Mean	Standard deviation
Coated NiTi	221.77	141.81
Coated SS	84.08	7.92
Coated TMA	112.74	4.83
NiTi	258.93	140.03
SS	84.88	6.11
TMA	245.56	61.76

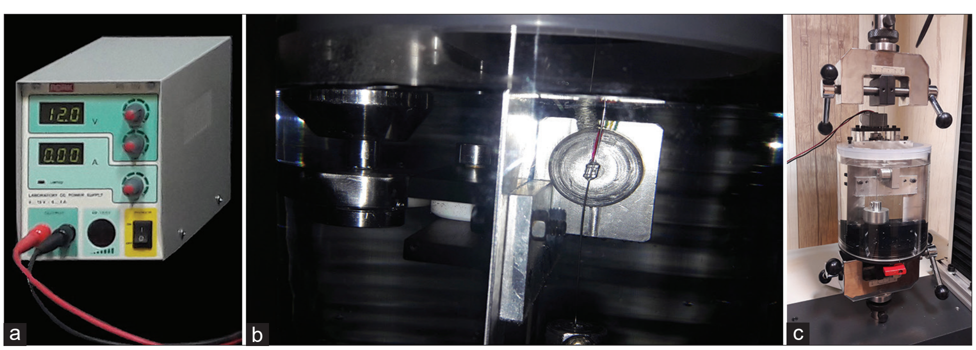

Figure 1.: (a) Transformer applying 12 v voltage; (b) fixture; (c) designed device to be positioned on the lower compartment of the universal testing machine

SEM images [Figure 5] revealed ZrO2 particles on the surface of TMA wires. Despite the change in surface roughness of the other two coated wires, ZrO2 was not detected on their surface. According to the EDX analysis, the amount of Zr on their surface was almost zero.

Static and kinetic friction

Tables 2 and 3 present the mean and standard deviation of kinetic and static friction of the six groups, respectively. Considering the normal distribution of static and kinetic friction data ($P > 0.05$), one-way ANOVA, independent t-test, and Tukey's test were applied for multiple and pairwise comparisons. A comparison of coated and non-coated wires revealed no significant difference in static and kinetic friction ($P > 0.05$). No significant difference was noted in static and kinetic friction, neither among different types of coated wires nor among different types of non-coated wires ($P > 0.05$).

Table 2: Mean and standard deviation of kinetic friction of the six groups

Group	Mean	Standard deviation
Coated NiTi	1.14	0.12
Coated SS	3.02	0.89
Coated TMA	2.77	0.31
NiTi	1.33	0.26
SS	2.63	0.57
TMA	2.85	0.55

Discussion

This study assessed the effect of ZrO2 nano-coating on friction resistance of different orthodontic wires. The results showed that although the AFM topography images confirmed the surface roughness of all three types of wires, statistical analysis indicated that changes in the surface roughness were only significant for TMA

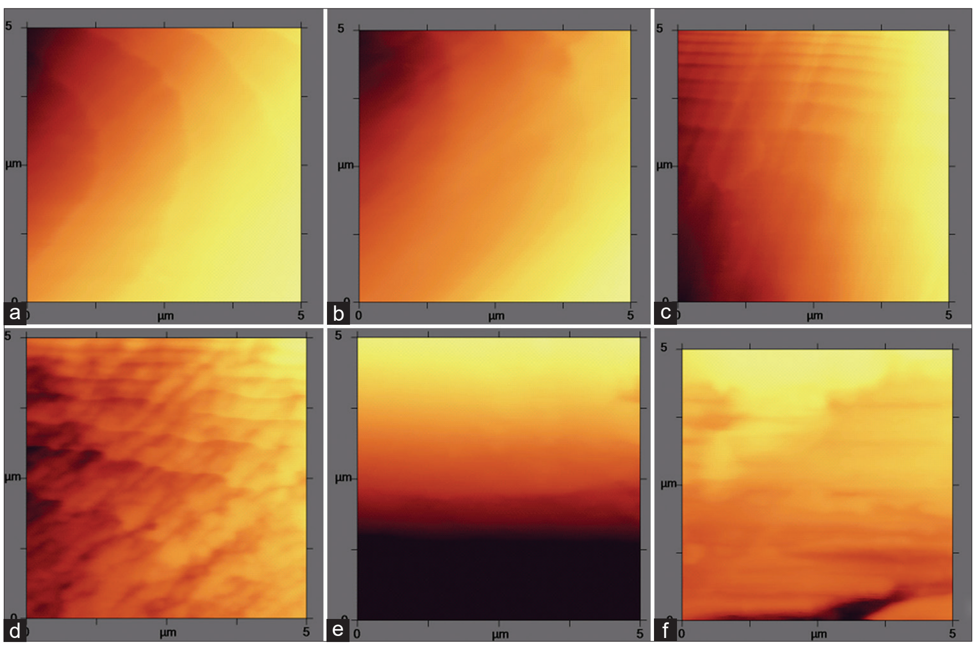

Figure 2: TopoFwd images (a) NiTi, (b) NiTi with coating, (c) SS, (d) SS with coating, (e) TMA, (f) TMA with coating

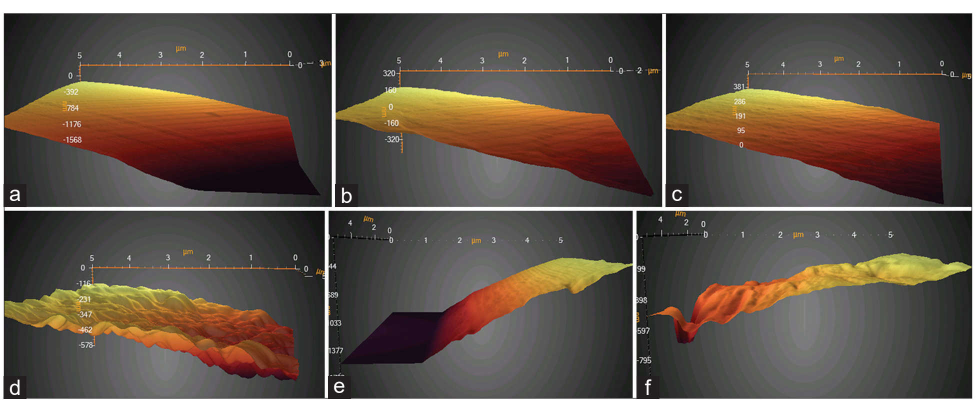

Figure 3: Three-dimensional images (a) NiTi, (b) NiTi with coating, (c) SS, (d) SS with coating, (e)TMA, (f) TMA with coating

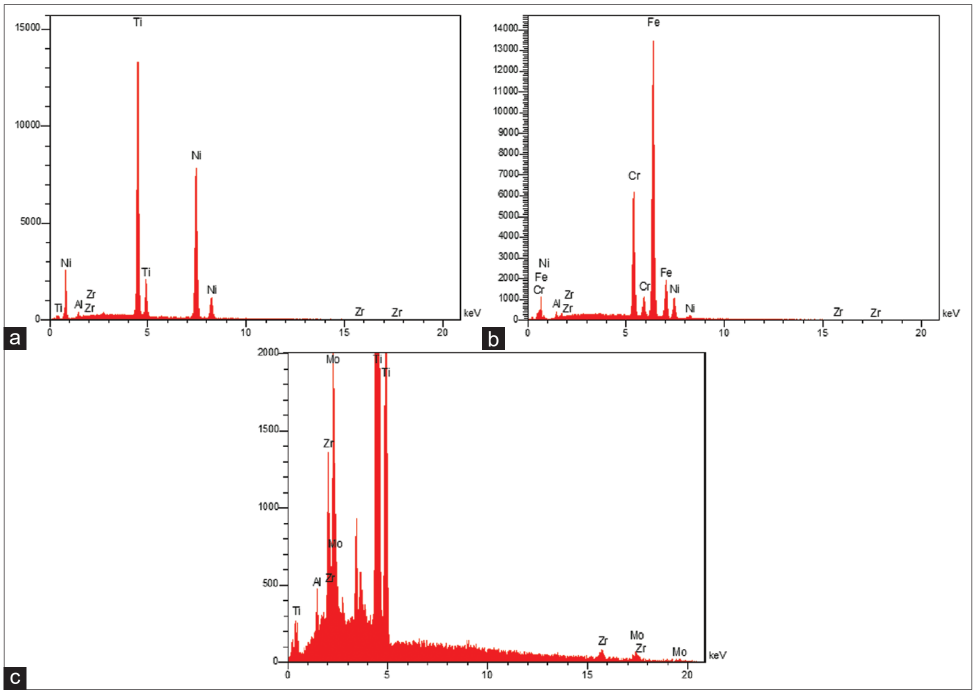

Figure 4: EDX (a) NiTi with coating, (b) SS with coating, and (c) TMA with coating

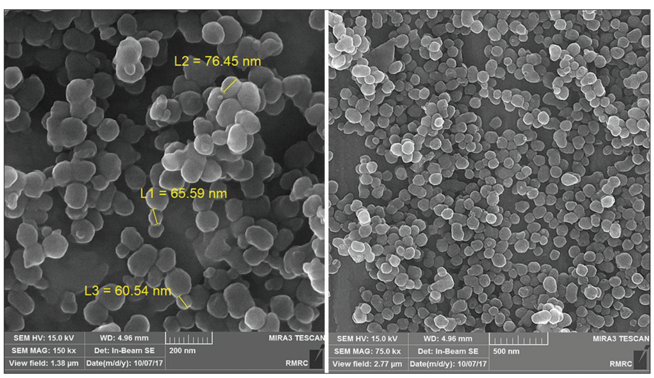

Figure 5: FESEM images of TMA coated wire at 200 and 500 nm magnifications

wires. EDX analysis and SEM images showed ZrO2 nano-coating only on the surface of TMA wires. Thus, it may be concluded that the sol-gel technique did not cause significant changes in terms of roughness due to the presence of a coating on the surface of the other two types of wires. Also, the sol-gel technique may be responsible for alterations in the surface roughness of NiTi and SS wires without ZrO2 nano-coating. According to Alavi *et al.*,[26] TMA wires have three elements of Sn, Zr, and Mo in their structure, which are not present in the composition of NiTi and SS wires. Davidson[20-22] used ZrO2 for coating orthopedic implants, guide wires, cardiovascular implants, catheters, and other surgical instruments. The coated surfaces were made of low-modulus metal cores or substrates such as zirconium or zirconium alloys. Accordingly, it may be hypothesized that the presence of Zr allows efficient coating of TMA wires with ZrO2.

Table 3: Mean and standard deviation of static friction of the six groups

Group	Mean	Standard deviation
Coated NiTi	1.81	0.20
Coated SS	4.90	1.28
Coated TMA	4.76	0.28
NiTi	1.99	0.35
SS	4.24	0.72
TMA	4.82	0.50

Due to significant changes in surface roughness of wires that underwent the sol-gel technique, all wires were evaluated in terms of static and kinetic friction. The assessments revealed that the difference in static friction of NiTi and SS wires (that underwent the sol-gel technique and expressed changes in surface roughness but did not retain their ZrO2 coating) was not significant when compared with non-coated NiTi and SS wires. The difference in kinetic friction was not significant either. Moreover, the TMA wires that experienced a significant change in surface roughness (and were the only wires that retained their ZrO2 coating) did not show a significant difference in static or kinetic friction either. Muguruma *et al.*[27] evaluated the effect of Diamond-Like Carbon (DLC) coating on friction, surface roughness, hardness, and elastic modulus of orthodontic wires. They compared NiTi and SS wires with DLC coating and three types of maxillary canine brackets, namely conventional SS and two types of self-ligating brackets. The results showed no significant difference in surface roughness of wires with and without DLC coating. On the other hand, increasing the slot angle caused a significant reduction in friction of wires coated with DLC compared with uncoated wires (friction test was performed at 0° and 10° angles). In their study, the surface roughness of coated samples was not significantly different, but DLC coating decreased the friction. In our study, despite the presence of a significant difference in surface roughness of TMA wires with and without coating, no significant difference was observed in friction between the two groups. Thus, it may be concluded that surface roughness does not necessarily translate to a change in friction. In our study, there was no color difference between the coated and non-coated TMA wires; whereas, some coatings such as DLC darken the wires.[28] In dentistry, aesthetics is highly important. Thus, the darkening of the wires by the DLC coating would be aesthetically unpleasant and is a drawback of this technique.

However, the friction-reducing effect of ZrO2 has been evaluated in some other fields, and some previous studies have confirmed its efficacy in the reduction of friction. Alavi *et al*.[26] assessed the TMA wires contained 62.74% Ti, 16.94% Mo, 10.39% Zr, and 9.93% Sn in their composition. Davidson[29] used a biocompatible titanium alloy with a low modulus of elasticity for orthopedic implants. This alloy had 10–20% Ti, 35–50% Nb, and up to 20% Zr. In Davidson's study,[20] the application of ZrO2 coating on the surface of titanium alloy decreased the friction but in the present study, the application of ZrO2 coating on the surface of TMA wires had no significant effect on friction. Different composition of the titanium alloys used in the two studies may explain the difference in the results regarding the effect of ZrO2 coating on friction.

Several studies have assessed the effect of different coatings on wire-bracket friction. However, what makes this study superior to the others is the simulation of occlusogingival movements of the teeth as well as the simulation of the oral environment by using artificial saliva. Also, we used different types of wires in our study while other studies only used one type[16,30-32] or two types[25] of wires. For instance, Redlich *et al*.[16] coated the wires with nickel-phosphorus electroless film dipped in IF-WS2 to minimize the friction between SS orthodontic wires and brackets. The coated wires were evaluated using SEM and subjected to EDS. The friction tests were carried out at 0°, 5°, and 10° angles in a universal testing machine. Moreover, the adhesion properties of coated wires were evaluated after the friction test using Raman spectroscopy. They concluded that the measured friction loads decreased by up to 54% in coated wires. Raman spectroscopy revealed that even after extensive friction tests, Ni-P with IF-WS2 nanoparticles remained attached to SS wires. Kachoei *et al*.[30] evaluated the antibacterial, mechanical, and physical properties of zinc oxide nano-coating on NiTi wires. They evaluated the physical properties using SEM and AFM; while, the mechanical properties were evaluated at 0°, 5°, and 10° angles in a universal testing machine. They concluded that zinc oxide nano-coating significantly improved the surface quality of NiTi wires in terms of antibacterial, mechanical, and physical properties.

In some studies, angulation plays no role in the simulation of friction.[32] Thus, the significant role of binding and physical notching parameters has been ignored in the creation of friction in such studies.[6,33]

In the majority of tests carried out to assess the effect of different coatings on wire-bracket friction, the effects of binding and physical notching parameters have been evaluated by changing the slot angle.[16,25,27,30,31] However, we performed the tests in the presence of artificial saliva under different angles, used different types of wires, and also simulated the occlusogingival tooth movements. Thus, the effect of binding and physical notching on friction was prominent in our study, and the obtained results are probably closer to reality and can be more accurately generalized to the clinical setting. Future studies are recommended to assess the effect of other coatings on the friction of orthodontic wires while employing superior techniques to better simulate the oral environment.

Conclusion

ZrO2 nano-coating could only be applied on TMA wires, and had no significant efficacy for reduction of static or kinetic friction of TMA wires.

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Conflicts of interest
Amin Golshah and Shirin Asadian Feyli declare that they have no conflict of interest.

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