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ORIGINAL ARTICLE

Comparison of static friction and surface topography of low friction and conventional TMA orthodontic arch wires: An in-vitro study

Nouf Alsabti *, **Nabeel Talic**

Department of Pediatric Dentistry and Orthodontics, College of Dentistry, King Saud University, Riyadh, Saudi Arabia

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KEYWORDS

Resistance to sliding;
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Abstract *Background:* Arch wire surface characteristics, especially surface roughness and topography, influence the coefficient of friction during sliding. The clinician should be familiar with the properties of orthodontic appliances and materials that could result in high friction to maximize the efficiency of treatment. This study aimed to compare the static friction of orthodontic arch wire materials, including a newly introduced low-friction TMA, conventional TMA, and stainless steel arch wires, using an Instron universal testing machine and to evaluate their surface topographical features using a noncontact optical profilometer.

Methods: A total of 30 arch wire specimens were used, including 10 low-friction TMA (TMA-Low), 10 conventional TMA (TMA-C), and 10 stainless steel (SS), (Ormco, Orange, CA, USA) measuring 0.016 × 0.022 in. The static frictional force of each arch wire material was measured using the universal Instron machine. The surface topography was evaluated using a noncontact profilometer machine.

Results: The static frictional resistance forces were highest in the TMA-C alloy group, and the value was statistically significant in comparison to the SS arch wire but not to the TMA-Low arch wire. The mean value of the static friction of the TMA-Low group was intermediate between the TMA-C and SS arch wires. However, this difference was statistically insignificant compared to the other two alloys. A surface roughness evaluation using a profilometer machine revealed that the highest mean of all three roughness parameters was found in the TMA-C group, followed by the TMA-Low and SS arch wires in descending order.

* Corresponding author.
E-mail address: Nouf_al-sabti@hotmail.com (N. Alsabti).

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Conclusion: The static friction resistance forces and surface roughness values of the TMA-Low arch wire are comparable to those of TMA-C but are still considered inferior to those of the SS arch wire.

1. Introduction

Friction is defined as "The function of the relative roughness of two interacting surfaces and results when the two relative surfaces move against each other" (Serway, 1982). The known friction comprises two basic types: static friction (SF) and kinetic friction (KF). Static friction refers to "The lowest force required to initiate orthodontic tooth movement when the two surfaces are statically related" (Omana, 1992). Kinetic friction is "The force that resists the movement of one object against another when a constant speed is applied" (Omana, 1992). Static friction is more significant than kinetic friction, as it is more difficult to change the position of an object over a surface than it is to maintain its movement against the surface (Omana, 1992). Furthermore, the kinetic friction in practical situations is not very relevant to orthodontic movement because it is very unlikely to have the teeth moving in a continuous motion along an arch wire. Instead, the process of sliding mechanics occurs very slowly, and it includes a sequential process that are close to equilibrium. During orthodontic tooth movement, static and kinetic friction are the outcomes of arch wire contact and its interaction with the orthodontic bracket or the ligating ligature. This resulting friction contributes to only a small part of the resistance to sliding (RS) during tooth movement (Kusy and Whitley, 1999). The phenomena of RS were previously divided into three components by Kusy and Whitley: "Classic friction (FR), binding (BI), and notching (NO), usually described as RS = FR + BI + NO" (Kusy and Whitley, 1999). The friction (static or kinetic) (FR) results from the arch wire contact with the bracket surface and occurs when the wire is in a passive status, meaning no angulation exists in relation to the bracket's slot (Kusy and Whitley, 1999).

Numerous studies have shown that SS arch wires have a smoother surface than TMA arch wires, and scanning electron microscopy has revealed that TMA wires have uniformly distributed pores and considerable surface roughness (Kusy et al., 1988; Krishnan and Kumar, 2004; Yu and Huang, 2011). The available evidence suggests that TMA arch wires are inferior to SS arch wires in sliding mechanics due to their physical, mechanical, and surface characteristics (Frank and Nikolai, 1980; Drescher et al., 1989; Angolkar and Kapila, 1990; Vaughan et al., 1995).

Arch wire surface characteristics, especially surface roughness and topography, influence the coefficient of friction during sliding (Yu and Huang, 2011). The surface roughness of dental materials is extremely important; it contributes to the surface contact area and, thus, has a great impact on the corrosive behavior and biocompatibility of the material (Bourauel et al., 1998). In addition, the surface roughness and topography of orthodontic arch wires influence the working characteristics of the wire during clinical use (Verstrynge et al., 2006). It has been shown that surface roughness has a critical effect on altering wire behavior during clinical use. It plays an important role in influencing the wire performance, biocompatibility, aesthetics, corrosion potential, and efficiency of orthodontic treatment (Kusy et al., 1988). Moreover, the amount of plaque buildup during clinical use of wires is influenced by the nature of its surface roughness, which in turn affects the biological contribution for increasing friction as described earlier (Wichelhaus et al., 2005).

Currently, orthodontic manufacturing companies claim to produce new low-friction materials and bracket systems to market their products. The proper selection of arch wires and an understanding of their mechanical behavior are very important for clinicians to achieve clinical success (Anto, 2012). Therefore, a clear understanding of the frictional forces, their impact on clinical orthodontic treatment situations, the variables that play a role in increasing friction and how to fully control it is very crucial for orthodontists to provide efficient and effective care for patients. In particular, the clinician should be familiar with the properties of the orthodontic appliances and materials that could result in high friction during sliding mechanics and how much of the applied force is expected to be lost due the resulting friction to maximize the efficiency of treatment. The aim of this study is to evaluate the static friction and surface topography of orthodontic arch wire materials, including a newly introduced low-friction titanium molybdenum alloy (TMA), conventional TMA, and stainless-steel arch wires, using the universal Instron machine and a noncontact profilometer machine.

2. Materials and methods

2.1. Universal Instron Machine (Measuring static friction)

2.1.1. Sample description

A total of 30 as-received arch wire specimens were used. The arch wires were classified into three groups based on the material type (10 low-friction TMAs, 10 conventional TMAs, and 10 SS). A straight arch wire with a size of 0.016 × 0.022-in. was used for all arch wire alloys. The static frictional force of each arch wire material was measured using the universal Instron machine. The conventional and low-friction TMA arch wires served as the test groups, while the SS arch wire served as the control group. A stainless steel bracket for the maxillary right bicuspid with a 0.018 × 0.025-in. slot dimension was used to ligate the arch wires. One bracket per group of wires were used (total of 3 brackets). The prescription of the brackets was standardized with −7° torque and 0° tip. The tests for all groups were carried out in a dry environment at an angulation of zero using a universal testing machine (Instron 5965, Instron Corp, Norwood, MA, USA). A new arch wire segment was used for each test. Elastomeric modules were used to tie the wires into the brackets. All tests were carried out by the same examiner.

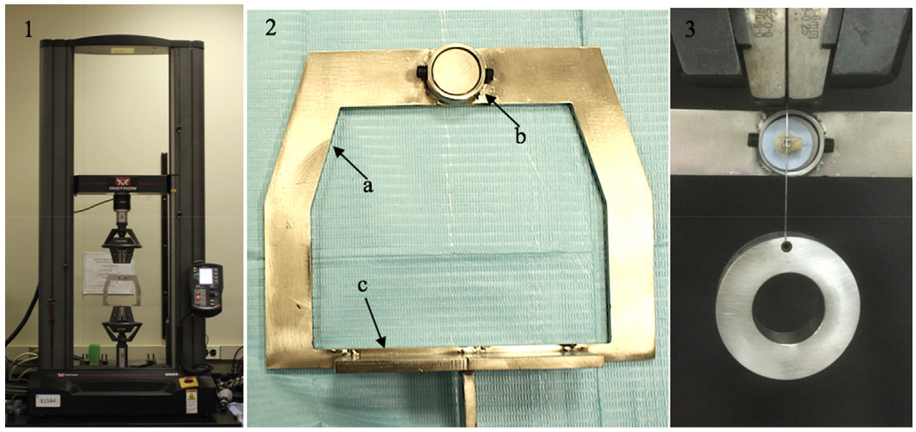

Fig. 1 Photographs showing (1) Universal testing machine (Instron 5965), (2) Custom made mounting device. (a) Outer Aluminum block. (b) Inner holder. (c) Anterior-posterior adjusting base, (3) 150-g weight attached to the lower end of the wire.

2.1.2. Experimental set up

2.1.2.1. Custom-made mounting device. A custom-made mounting device was constructed to be attached to the base of the Instron machine. The design of this device was adopted from the previously used technique (Redlich et al., 2003). The device involved an outer aluminum block measuring 20 cm in height and 15 cm in width that was attached to an anterior-posterior adjustment base. The outer block contained an inner holder where the acrylic base (holding the bracket-wire assembly) was secured at an angulation of zero inside the mounting device using two attached screws. A 150-g weight was constructed to be attached to the lower end of the wire to maintain tension during the test (Fig. 1).

2.1.2.2. Arch wire sliding test. Wires (Ormco, Orange, CA, USA) measuring 0.016 × 0.022 in. were cut into 7-cm-long segments and debris was cleaned off with 95% ethanol. To define the area of ligation for the brackets, a mark approximately 3.5 cm from the lower end of each wire was drawn using a permanent marker. Each wire was ligated into a straight SS bracket (Ormco), measuring 0.018 × 0.025 in., bonded to the corresponding acrylic tooth with an elastomeric module using a Mathieu hemostat, and then immediately tested by the same investigator. A custom-made mounting device was stabilized in the Instron machine in the anterior-posterior position for testing the entire sample. The upper end of the wire was fixed to the machine load cell (5 kN) using the guiding groove, and an acrylic base (holding the bracket-wire assembly) was secured at an angulation of zero inside the mounting device using two attached screws. To maintain tension during the test, a 150-g weight was fixed to the lower end of the wire. The test was then started by drawing the arch wire upward through the bracket at a cross-head speed of 5 mm/min for 2 min. The computer software, attached to the Instron machine, recorded the static frictional resistance generated between the bracket and wire on an XY graph. The X-axis recorded the wire movement in millimeters per second (mm/s); the Y-axis recorded the frictional resistance force between the bracket and the arch wire in Newtons (N), which will be converted into grams. The static frictional force was obtained as the highest peak force encountered during the first millimeter of wire displacement in the load-displacement graph. All specimens were tested in the same way after calibrating the Instron machine to the starting position. All tests were conducted in a dry environment.

2.2. Optical profilometer, surface topography analysis

2.2.1. Sample description

A total of 30 as-received arch wire specimens were used for the profilometric scans {10 low-friction TMA (TMA-Low), 10 conventional TMA (TMA-C), and 10 stainless steel (SS)}, (Ormco, Orange, CA, USA) measuring 0.016 × 0.022 in. The conventional and low-friction TMA arch wires served as the test groups, while the SS arch wire served as the control group. The surface topography measurements of each arch wire were measured with an optical surface profiling system (Bruker Contour GT- K, Bruker Nano GmbH, Berlin, Germany), which used noncontact scanning white light interferometry to evaluate the 2D surface configuration and roughness.

2.2.2. Experimental setup

Nine different regions from each arch wire specimen were randomly selected from a canine-to-canine segment for profilometric scans. The profilometric scan area measured approximately 0.95 × 1.2 mm using an objective standard camera at 5× magnification. To control the precision and measurement of the surface roughness parameters, data were processed using Vision 64 application software (Bruker Contour GT-K, Bruker Nano GmbH, Berlin, Germany). Three surface topography parameters were examined, including the arithmetic average height (i.e., average roughness; Sa), root mean square (Sq), and ten-point height (Sz). The scanning distance was set at 5 mm.

3. Statistical analysis

The statistical analysis was undertaken using SPSS software (IBM SPSS Inc., version 20, Chicago, IL, USA), and the level of significance was set at $P < 0.05$. Assuming an effect size of $f = 0.6$ (Cohen, 1988), with $\alpha = 0.05$ and $\beta = 0.20$ (power 80%), the needed sample size was 10 samples in each of the

3 groups. Descriptive data including the means, standard deviations, and minimum and maximum readings were calculated for the comparison of the all groups. The differences between the weighted means were analyzed with one-way ANOVA, and group differences were then analyzed with Tukey's post hoc comparisons test.

4. Results

4.1. Static frictional values obtained using a universal Instron machine

Static frictional resistance forces were measured and obtained. Descriptive statistics show that the highest mean static friction was found in the TMA-C group, followed by the TMA-Low and SS arch wires in descending order (Table 1). The comparison of the mean values of static friction across the three types of wires (TMA-C, TMA-Low, and SS) shows a statistically significant difference ($p = 0.002$), (Table 1). The Tukey's post hoc test among the three mean values indicates that the static friction of TMA-C is statistically significantly higher than the mean value of the SS arch wire, while no significant difference was found with the TMA-Low arch wire. Additionally, no statistically significant difference was found between the TMA-Low and SS arch wires (Table 2).

4.2. Optical profilometer

The surface topography and roughness of the three arch wire types were examined using an optical profilometer (Fig. 2). Three roughness parameters were obtained, and a comparison between each arch wire type for each parameter was performed. Descriptive statistics show that the highest mean of all three roughness parameters was found in the TMA-Low group, followed by the TMA-C and SS arch wires in descending order (Fig. 3, Table 3). The mean values of the roughness parameters across the three types of wires (TMA-C, TMA-Low, and SS) were compared and are shown below.

4.2.1. Arithmetic average height of the surface topography (average roughness, Sa)

There was a statistically significant difference in the mean values of the average roughness (Sa) among the three types of arch wires (TMA-C, TMA-Low, and SS) ($p = 0.011$) (Table 3). The Tukey's post hoc shows that among the three arch wires, the average roughness mean value of the SS material was statistically significantly lower than the mean values of the other two arch wire types (TMA-C and TMA-Low). However, there was no statistically significant difference in the mean values of the average roughness of the TMA-C and TMA-Low arch wire materials.

4.2.2. Root mean square of the surface topography (Sq):

There was a statistically significant difference in the mean values of the root mean square (Sq) among the three types of arch wires (TMA-C, TMA-Low, and SS) ($p = 0.000$) (Table 3). The Tukey's post hoc test shows that among the three arch wires, the root mean square mean value for the SS material is statistically significantly lower than the mean values for the other two arch wire types (TMA-C and TMA-Low). However, there was no statistically significant difference in the mean values of the root mean square of the TMA-C and TMA-low arch wire materials.

4.2.3. Ten-point height (mean peak to valley height) of the surface topography Sz

There was a statistically significant difference in the mean values for the ten-point height (Sz) among the three types of arch

Table 1 Descriptive statistics and one-way of variance analysis to compare the mean values of maximum force peak across the three arch wires.

Type of wire	N	Mean	Std. Deviation	Minimum	Maximum
Conventional TMA	10	1.0630	0.55650	0.60	2.20
Low TMA	10	0.6500	0.39158	0.30	1.50
Stainless steel	10	0.3510	0.10137	0.25	0.60
	Sum of Squares	df	Mean Square	F-value	p-value
Between Groups	2.556	2	1.278	8.102	0.002
Within Groups	4.260	27	0.158		
Total	6.816	29			

Table 2 Comparisons of mean values of maximum force peak across the three arch wires.

Type of wire	Type of wire	*Mean Difference*	Std. Error	*Sig.*	Lower Bound	95% Confidence Interval Upper Bound
Conventional TMA	Low TMA	0.413	0.177	0.069	−0.0274	0.853
	Stainless steel	0.712*	0.177	0.001**	0.271	1.152
Low TMA	Conventional TMA	−0.413	0.177	0.069	−0.853	0.0274
	Stainless steel	0.299	0.177	0.230	−0.141	0.739
Stainless steel	Conventional TMA	−0.712*	0.177	0.001**	−1.152	−0.271
	Low TMA	−0.299	0.177	0.230	−0.739	0.141

** The mean difference is significant at the 0.01 level.

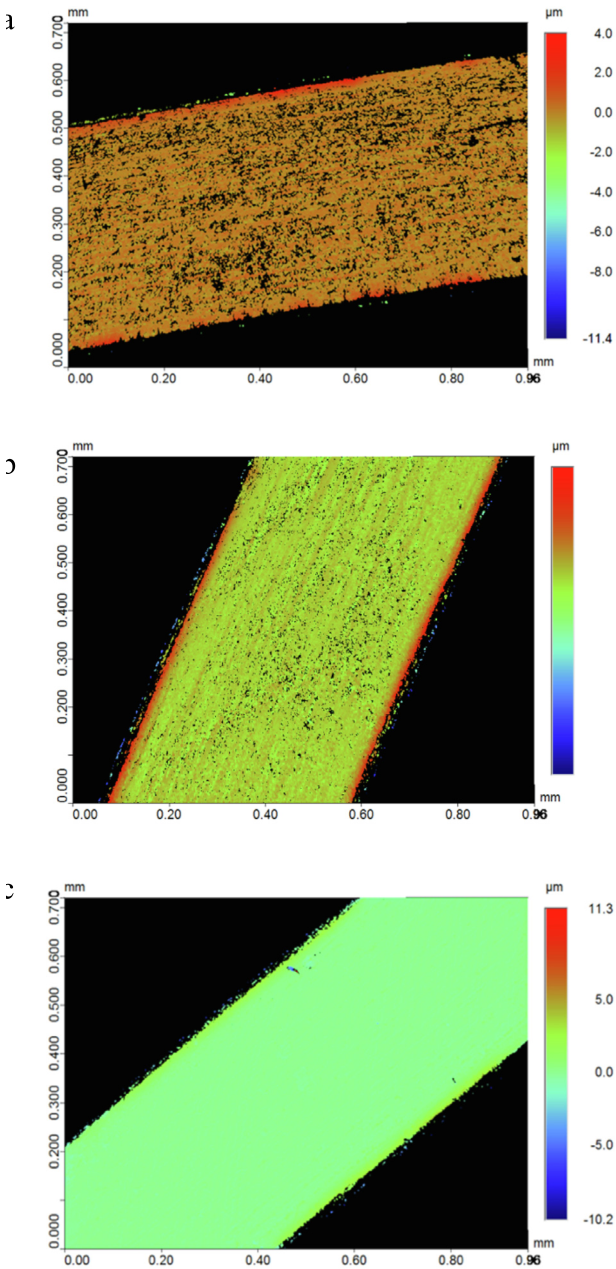

Fig. 2 Surface topographical images of the arch wire surfaces obtained by optical profilometer. (a) (TMA-C) Conventional TMA arch wire: (TMA-Low) low-friction TMA arch wire, (c) (SS) stainless steel arch wire.

wires (TMA-C, TMA-Low, and SS) ($p = 0.000$) (Table 3). The pairwise comparison of the mean values shows that among the three materials, the ten-point height mean value of the SS material is statistically significantly lower than the mean values of the other two arch wire types (TMA-C and TMA-Low). However, there was no statistically significant difference in the mean values of the ten-point height of the TMA-C and TMA-Low arch wire materials.

5. Discussion

This study was conducted to evaluate the resistance to sliding and surface topographical features of a newly introduced material (TMA-Low arch wire) and compare its properties to the other two types of alloys (TMA-C and SS arch wires). The arch wire investigated in this study was introduced in 2014 by the Ormco company. To the best of our knowledge, this new material has not yet been tested, and no published studies have investigated the frictional and surface topographical properties of this new arch wire. The TMA-C and TMA-Low arch wires served as the test groups, while the SS arch wire served as the control group, as the SS material has always been considered by researchers as the reference material to assess and compare the characteristics of new arch wires in the field (Verstrynge et al., 2006).

In the first part, the static friction was evaluated using the universal Instron machine. The measured static frictional resistance force refers to the force required to initiate orthodontic tooth movement. The test was carried out in a passive configuration because it was intended only to measure the first component of RS in the early stages of sliding, which is the classic friction. This machine was previously considered the standard method and the conventional way of testing the resistance to sliding in most of the previously reported studies that used this method (Cha et al., 2007; Chang et al., 2013; Choi et al., 2014; Doshi and Bhad-Patil, 2011; Loftus, 1999; Parmagnani and Basting, 2012; Regis, 2011; Saunders and Kusy, 1994; Vaughan, 1995; Redlich et al., 2003; Downing et al., 1994).

The results of this study showed that the highest static frictional resistance forces were found in the TMA-C alloy group compared to the other two alloy (TMA-Low and SS) arch wires. This difference was statistically significant compared to the SS arch wire but not to the TMA-Low arch wire. The mean value of static friction for the TMA-Low group was intermediate between the TMA-C and SS arch wires. However, this difference was statistically insignificant compared to the other two alloys. This is similar to the results shown in the orthodontic literature, as previous studies reported that TMA arch wires exhibited the highest frictional values when compared to stainless steel wires (Andreasen and Quevedo, 1970; Frank and Nikolai, 1980; Drescher et al., 1989; Angolkar and Kapila, 1990; Kapila et al., 1990; Vaughan et al., 1995).

Additionally, the results are similar to those of multiple studies in the literature that evaluated the frictional values of different introduced TMA arch wires with improved surface finish in which modified TMA products showed no advantage over the SS arch wire (Drescher et al, 1989; Tidy and Orth, 1989; Burstone and Farzin-Nia, 1995).

The profilometric scans revealed that the stainless steel arch wire showed the smoothest surface topography among the other alloys and had a statistically significantly lower roughness value for all the examined roughness parameters. The TMA-Low arch wire showed the highest roughness value and was not statistically significantly different than the TMA-C roughness value. The results of the profilometric scans in our study revealed similar findings to those of previously reported studies in which the SS arch wire surface exhibited

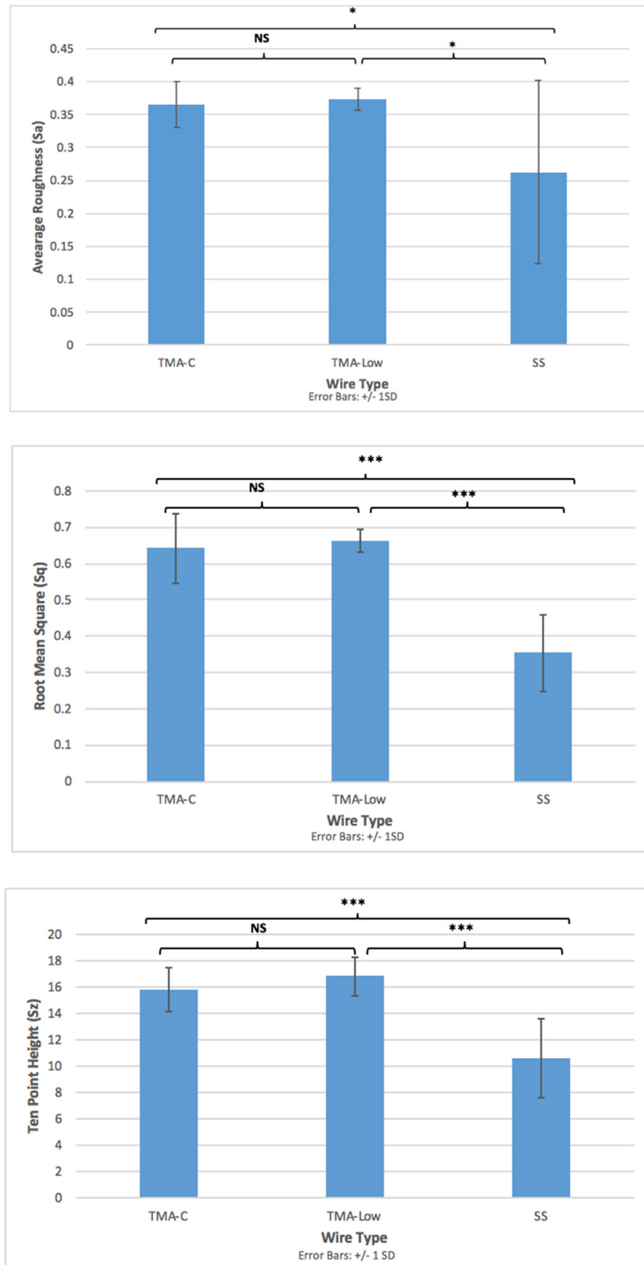

Fig. 3 Bar graphs comparing the average mean values of the average roughness (Sa), root mean square (Sq), and ten-point height (Sz) parameters obtained using profilometer among the three arch wire groups, NS, Non-significant, * $P < 0.05$ *** $p < 0.001$.

the least roughness values (Kusy et al., 1988; Bourauel et al., 1998; Krishnan and Kumar, 2004; Yu and Huang, 2011; Anto, 2012).

As with the majority of studies, the current study is subject to limitations. The first limitation of our study is that the friction was tested in a dry environment only. Future research on the newly developed TMA arch wire (TMA-low) might extend the explanations of the wet state effect on the frictional characteristics of these arch wires. However, it should be noted that artificial saliva does not have viscosity and wettability properties similar to those of human saliva. Hence, it is advocated to use human saliva to investigate the lubricous effect on the frictional resistance of TMA arch wires in the future. It should also be acknowledged that testing in a dry state has been shown to rank next to testing in a wet state utilizing human saliva, which may ameliorate the shortcoming of not testing in a wet environment in this study (Al-Mansouri et al., 2011). Furthermore, these beta titanium-based arch wires are known to exhibit abrasive wear during clinical use as a consequence of the high reactivity of the wire's surface. Hence, the treated surface finish of the modified wire could be subjected to deterioration in clinical practice, which subsequently would have an influence on its frictional properties (Kusy et al, 1991; Kusy et al, 2004). Therefore, it is recommended that the potential effects of the oral environment on the frictional properties of this new product during the sliding stage are considered in future clinical trial studies.

Table 3 Descriptive statistics and one-way of variance analysis to compare the mean values of outcome variables among the three types of materials (Profilometer).

		N	Mean	Std. Deviation	Minimum	Maximum
Average roughness (Sa)	Conventional TMA	10	0.365	0.0346	0.301	0.418
	Low TMA	10	0.373	0.0166	0.343	0.406
	Stainless steel	10	0.262	0.1397	0.140	0.600
	Total	30	0.333	0.0955	0.140	0.600
Root mean square (Sq)	Conventional TMA	10	0.641	0.0970	0.459	0.779
	Low TMA	10	0.662	0.032	0.614	0.727
	Stainless steel	10	0.354	0.106	0.223	0.551
	Total	30	0.552	0.165	0.223	0.779
Ten Point height (Sz)	Conventional TMA	10	15.803	1.668	13.180	18.819
	Low TMA	10	16.806	1.496	14.598	19.814
	Stainless steel	10	10.572	3.016	6.292	15.879
	Total	30	14.394	3.480	6.292	19.814
		Sum of Squares	df	Mean Square	F-value	p-value
Average roughness (Sa)	Between Groups	0.076	2	0.038	5.404	0.011
	Within Groups	0.189	27	0.007		
	Total	0.265	29			
Root mean square (Sq)	Between Groups	0.595	2	0.297	40.744	0.000
	Within Groups	0.197	27	0.007		
	Total	0.792	29			
Ten Point height (Sz)	Between Groups	224.109	2	112.055	23.804	0.000
	Within Groups	127.098	27	4.707		
	Total	351.207	29			

The second limitation concerns the use of a universal Instron machine, as it does not clearly simulate actual complex tooth movement (Drescher et al, 1991). Therefore, our study was extended to comprehensively evaluate actual tooth movement using an orthodontic measurement and simulation system (OMSS) machine.

6. Conclusion

- The mean values of the static frictional resistance forces showed that an arch wire constructed from TMA-C exhibited the highest value of static friction followed by TMA-Low and SS arch wires in descending order, with a significant difference only found between the TMA-C and SS groups.
- Profilometric scans showed that the SS arch wire revealed the smoothest surface topography, and the roughness values were statistically significantly lower than those of the other arch wire alloys (TMA-C and TMA-Low). The TMA-Low arch wire surface topography exhibited a rougher surface than the SS material and was still considered to be inferior to the SS arch wire.
- The frictional values of the TMA-Low arch wire indicate that it is still considered inferior to the SS arch wire and that the SS arch wire remains the mainstay of orthodontic mechanotherapy.

Ethical statement

Ethical approval was obtained from King Saud University, College of Dentistry Research Center (PR 0073).

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CRediT authorship contribution statement

Nouf Alsabti: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Visualization, Writing - original draft. **Nabeel Talic:** Conceptualization, Methodology, Supervision, Project administration, Writing - review & editing.

Declaration of Competing Interest

N. Alsabti and N. Talic certify that there is no actual or potential conflict of interest in relation to this article.

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