Frontiers in Dentistry

Effect of Elastomeric Module Degradation and Ligation Methods on Kinetic Friction between NiTi or Stainless Steel Wires and Stainless Steel Brackets

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Article Info

Article type:
Original Article

Article History:
Received: 30 Mar 2023
Accepted: 30 Jul 2023
Published: 14 Mar 2024

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ABSTRACT

Objectives: The reduction of resistance to sliding between the archwire and bracket promotes more seamless tooth movement, leading to a faster and improved orthodontic treatment experience. This research aimed to examine how the degradation of elastomeric modules, different ligation methods, bracket-wire angle, and wire type (nickel titanium, NiTi or stainless-steel, SS) impact the kinetic friction resulting from the interaction between NiTi or SS archwires and SS brackets.

Materials and Methods: The current in vitro study was conducted on nine groups, including NiTi and SS archwires with three types of ligations (O-ring, figure of 8, and SS wire ligature) and two bracket-wire angles (0° and 10°). The kinetic friction in each group was measured using a Universal Testing Machine at four time intervals: baseline, day one, week one, and week four. Repeated measures ANOVA, Mauchly test of sphericity followed by the Greenhouse-Geisser test, and relevant post hoc tests were used for statistical analysis ($P<0.05$).

Results: The authors found a decrease in kinetic friction in all types of ligations, which confirmed the effect of time on the degradation of ligation modules. The kinetic friction of figure of 8 ligations was higher than both O-ring and SS wire ligations. No difference was observed between O-ring and SS wire ligations. Furthermore, the bracket-wire angle did not affect friction.

Conclusion: The authors suggest that the use of figure of 8 ligations in NiTi and SS wires should be limited due to their high friction and replaced with other types of ligations, if possible.

Keywords: Orthodontic Wires; Orthodontic Friction; Orthodontic Brackets

➢ **Cite this article as:** Ebrahimi P, Nastarin P, Hadilou M, Karimzadeh B, Kachoei M. Effect of Elastomeric Module Degradation and Ligation Methods on Kinetic Friction between NiTi or Stainless Steel Wires and Stainless Steel Brackets. *Front Dent.* 2024:21:10.

INTRODUCTION

In fixed orthodontics, tooth movement occurs using brackets and archwires through sliding or frictionless (utilizing loops) methods. It takes place when the force exerted is greater than the amount of frictional force and binding between the bracket slot and archwire [1]. In the sliding method, the friction between the wire and the bracket consumes almost 12% to 60% of the orthodontic force, necessitating the exertion of additional force to overcome the friction. This might cause anchorage loss and increase the risk of tooth root resorption [2,3]. According to the literature, factors affecting the friction between the wire and the bracket include the archwire material, its dimensions, surface structure, the angle of the wire and bracket slot [4,5], bracket type [6,7], ligation techniques [8], and saliva [9]. Also, the amount of force applied by the ligation is one of the factors affecting the amount of wire and bracket friction in an orthodontic system. This force has been reported in most studies to be 50 to 300 grams [10-13].

Various methods have been introduced to reduce frictional force, such as changing the size and material of the wire, changing the design of the bracket, wire surface coverage with different materials [14], application of lubricants [15], and using different types of ligatures and different methods of ligation [16]. It has been stated that the various techniques of ligation in elastomeric ligatures might alter the amount of friction by making complete or incomplete contact with the archwire [17].

As aforementioned, different ligatures and ligation types affect the amount of friction. There are two common ligatures widely used by orthodontists: 1) Elastomeric modules and 2) Stainless Steel (SS) wire ligatures [18]. Elastomeric ligatures are made of polyurethane rubber. These materials replaced latex rubber elastics due to the possibility of causing allergic reactions [19,20]. Various intraoral factors like chemicals present in food, saliva, and dentifrices can affect the properties of elastomeric modules. Also, their characteristics can be changed by temperature alterations due to the consumption of hot or cold food. Furthermore, elastomeric modules degrade in the oral environment, and the amount of force applied by them decreases over time. As a result, the friction between the wire and the bracket can be affected [21-24].

Regarding the wire alloy, it has been stated that SS wires provide a complete and stable connection between the orthodontic bracket and the wire. However, they create a significant amount of friction during archwire sliding [18]. On the other hand, Nickel Titanium (NiTi) wires are more flexible and exert light forces. They also have super-elasticity and shape memory characteristics [25]. However, some authors have stated that the friction caused by NiTi archwires is greater than stainless steel [3].

Edwards et al. [26] compared the amount of static frictional resistance between SS brackets and archwires among four ligation methods of elastomeric modules. They found that the friction created by “O-ring: figure of 8” ligations was the greatest in both dry and wet conditions [26]. In another study, Khambay et al. [27] found no consistent pattern of frictional forces between SS brackets and wires using different ligations of elastomeric modules. However, SS wire ligatures created lower friction between Titanium molybdenum alloy wires and SS brackets. Regarding the angle of bracket-wire, Jang et al. [28] found that the friction increased at higher angles. However, another study by Samorodnitzky-Naveh et al. [29] presented otherwise.

Demonstrated evidence suggests that minimizing friction between the archwire and bracket promotes more efficient tooth movement, accelerating and improving the overall quality of orthodontic treatment. However, there is a lack of research focusing on friction across different ligation techniques, particularly concerning the use of NiTi archwires. To provide sufficient information to help select the best ligation method in terms of frictional properties, the authors aimed to study the effect of the degradation process of elastomeric modules and different ligation methods on the friction between NiTi and SS wires with SS brackets. To the authors’ knowledge, there are no previous studies on this subject.

MATERIALS AND METHODS

Study settings:

This study was conducted in the Faculty of Dentistry, Tabriz University of Medical Sciences. The study design and protocols were approved by the Institutional Ethics Committee of Tabriz University of Medical Sciences (IR.TBZMED.VCR.REC.1399.033).

Sample size:

To determine the sample size, the authors used the proposed protocol in a systematic review and meta-analysis by Savoldi et al. [30] who evaluated the methodology of studies on the friction between brackets and archwires. A total of 90 samples (10 samples in each of the 9 groups) were prepared.

Study groups Each sample unit in the study consisted of 2 brackets adhered to a metal plate with an archwire tied by ligatures. The materials used to prepare the sample units were:

1. One hundred eighty standard 0.022-inch right and left lower central incisor teeth SS brackets (Ortho Organizers, California, USA) (two brackets for every sample unit). One right side and one left side bracket were used for each sample.
2. Two types of wires, including 60 round 0.016-inch NiTi wires (Skyortho, Yancheng,

China), and 30 straight 0.019×0.025 inch SS wires (American Orthodontics, Wisconsin, USA), both in 18 cm pieces.

3. Two types of ligature materials, including elastomeric module (Ortho Technology, Florida, USA) and SS wire ligature wires (Ortho Technology, Florida, USA).

Each sample unit consisted of one right and one left bracket. Both brackets were ligated with the same ligating method in each sample (Figure 1). Elastomeric modules were ligated in two ways, including "O-ring" and "figure of 8". Also, 0˚ and 10˚ wire-bracket angles were used for NiTi wires and 0˚ for SS wires. In 0˚ bracket-wire angle positioning, two brackets were placed in a parallel situation. In the 10˚ bracket-wire angle, the angle of one bracket was zero and the angle of the second bracket was 10˚ relative to the wire and the first bracket. The centers of all brackets' slots were in a straight line (Figure 1).

The groups were arranged as follows:

1. Ten sample units composed of a round 0.016-inch NiTi wire inserted into two SS brackets, both ligated with "O-ring" elastomeric ligatures. The angle between the two brackets was 0˚ (NiTi/0˚/O-ring).
2. Ten sample units consisting of a round 0.016-inch NiTi wire inserted into two SS brackets, both ligated with "O-ring: figure of 8" elastomeric ligatures. The angle between two brackets was 0˚ (NiTi/0˚/fig8).
3. Ten sample units made up of a round 0.016-inch NiTi wire inserted into two SS brackets, both ligated with SS wire ligatures. The angle between the two brackets was 0˚ (NiTi/0˚/SS-lig).
4. Ten sample units made up of a round 0.016-inch NiTi wire inserted into two SS brackets, both ligated with "O-ring" elastomeric ligature, and the angle between the two brackets was 10˚ (NiTi/10˚/O-ring).
5. Ten sample units composed of a round 0.016-inch NiTi wire inserted into two SS brackets, both ligated with "O-ring: figure of 8" elastomeric ligatures. The angle between the two brackets was 10˚ (NiTi/10˚/fig8).
6. Ten sample units consisting of a round 0.016-inch NiTi wire inserted into two SS brackets, both ligated with SS wire ligatures. The angle between the two brackets was 10˚ (NiTi/10˚/SS-lig).
7. Ten sample units made up of a rectangular 0.019×0.025-inch SS wire inserted into two SS brackets, both ligated with "O-ring" elastomeric ligatures. The angle between the two brackets was 0˚ (SS/0˚/O-ring).
8. Ten sample units composed of a rectangular 0.019×0.025-inch SS wire inserted into two SS brackets, both ligated with "figure of 8" elastomeric ligatures. The angle between the two brackets was 0˚ (SS/0˚/fig8).
9. Ten sample units consisted of a rectangular 0.019×0.025-inch SS wire inserted into two SS brackets, both ligated with SS wire ligatures. The angle between the two brackets was 0˚ (SS/0˚/SS-lig).

The authors used the "wire type/bracket-wire angle/ligation type" format in the rest of the article to identify groups more easily and avoid text prolongation.

Sample preparation:

The entire process of sample unit preparation was conducted by an experienced orthodontist. The brackets were attached perpendicular to the longitudinal axis of rectangular aluminum plates according to the aforementioned groups with cyanoacrylate adhesive (3M liquid superglue, USA). The distance between the two brackets was 10mm, and both of the brackets had 0˚ standard torque. Then, the aluminum plate was connected with two screws to the base of the Universal Testing Machine (H5K-S, Hounsfield Test Equipment Ltd., Redhill, UK) horizontally to perform sliding movements in order to measure kinetic friction (Figure 2). A 150-gram weight was hung from the bottom of the wire, and the upper part of the wire was connected to the arm of the machine. To simulate sliding movement, the arm stretched the upper part of the wire at a speed of 0.5 mm/s for 20 seconds, and the force was measured by the machine and recorded in computer software.

To simulate the degradation of elastic modules, all samples were stored in artificial human saliva at a temperature of 37˚ Celsius for one day, one week, and four weeks after sample unit preparation in an incubator. The artificial saliva was prepared according to the formula suggested by Christersson et al. [31]. It was a carboxymethylcellulose (CMC) based saliva made up of CMC (500mg), potassium phosphate (35mg), xylitol (3mg), sodium fluoride (20mg), potassium chloride (120mg), and sodium chloride (90mg) (Sigma-Aldrich Inc. St. Louis, United States) in a 100 mL water solution. The rationale for using artificial saliva was that a large amount of saliva was needed to store samples. However, during the application of the friction evaluation tests, fresh, natural unstimulated human saliva was provided in the morning immediately prior to the tests from one of the authors who had no periodontal problem, systemic disease, restoration, decayed teeth, and orthodontic appliances. The saliva was poured by pipette at a rate of 1ml/min at the point of contact between the wire and the brackets. In total, the tests were performed immediately after the sample preparation day (Baseline), and one day, one week, and four weeks later.

The computer connected to the universal machine began recording after 0.1 seconds of wire movement, so only dynamic frictional force was measured. Furthermore, because the transferred force by NiTi wires might have alterations in different temperatures, to maintain a consistent temperature, the authors used the Mardon thermally controlled system (KEMG Inc. Tehran, Iran). It consisted of a heater covering the samples, and a digital thermometer with a special heat-sensitive probe, controlling the temperature produced by the heater with an accuracy of one degree Celsius. Also, a wooden box was used to ensure a constant ambient temperature.

Fig. 1: Positioning of brackets on aluminum plates

Statistical analyses:

The amount of friction in each group was reported as mean±standard deviation (mean±SD). To analyze the effect of time, wire type, and archwire-bracket angle on the frictional force, the authors used repeated measures ANOVA. Significant results of the Mauchly test of sphericity were followed by the Greenhouse-Geisser test for statistical correction. Appropriate post hoc analysis was carried out when necessary. P<0.05 was considered significant.

RESULTS

The mean values and standard deviation for kinetic friction over time for each ligation method for the NiTi archwires are shown in Table 1. The results of the repeated measures ANOVA test showed that the interaction of time and ligation method (F=1.95, P=0.097), and the interaction of time and bracket-archwire angle (F=2.47, P=0.067) were not statistically significant.

However, the effect of time on the mean frictional forces, after considering the Greenhouse-

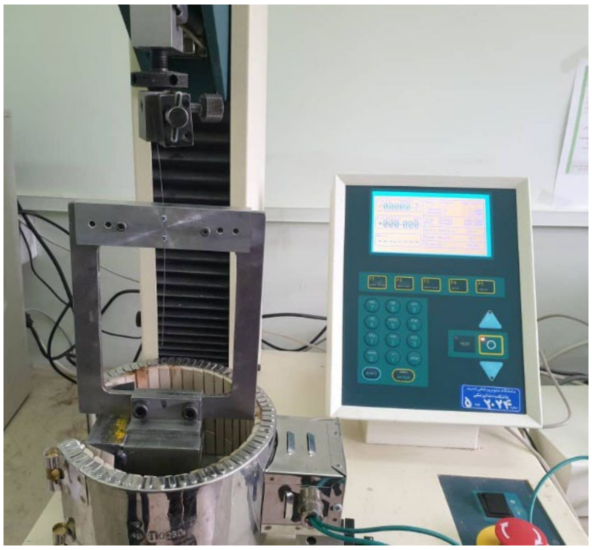

Fig. 2: Attachment of the aluminum plate to the base of the Universal testing machine. The aluminum plate was surrounded by MARDON heater

Table 1: The mean values ± standard deviation of kinetic friction (N) over time for each group of nickel titanium wires

Angle	Ligation Method	Baseline	Day 1	Week 1	Week 4
0°	**O-ring**	6.78±1.75	6.54±0.44	6.02±0.48	5.54±0.35
	Figure of 8	7.11±0.25	7.21±0.24	7.09±0.36	6.79±0.33
	Stainless steel ligature	6.22±0.28	6.42±0.24	6.36±0.23	6.12±0.17
10°	**O-ring**	6.33±0.36	6.41±0.46	6.34±0.11	6.37±0.28
	Figure of 8	7.4±0.22	7.36±0.09	7.21±0.35	7.02±0.41
	Stainless steel ligature	5.95±0.33	6.52±0.53	6.44±0.49	6.08±0.8

Table 2: The results of the Bonferroni post hoc test for different ligation methods in nickel titanium wires

Group (I)	(J)	Mean difference (I-J)	95% Confidence interval	P
O-ring	**Figure of 8**	-0.857	(-1.06; -0.65)	<0.001
	Stainless steel ligature	0.028	(-0.18; 0.23)	0.999
Figure of 8	**Stainless steel ligature**	0.885	(0.68; 1.09)	<0.001

Geisser correction, was statistically significant (F=7.54, P<0.001), and the analysis showed that the frictional force decreases as time goes forward (Figures 3,4,5). The results of the repeated measures ANOVA test showed no statistically significant change in the amount of frictional force after changing the angle between the archwire and bracket from 0 to 10 degrees (P=0.141). However, the mean frictional force had a statistically significant difference among the different ligation methods (P<0.001) (Figure 3). Immediately after ligation, the frictional forces were at the highest level in the "figure of 8" and the lowest level in the ligature wire group. However, one day, one week, and four weeks after ligation, the figure of 8 groups had the greatest frictional force and the O-Ring group had the lowest friction. Figures 4 and 5 demonstrate the changes in the frictional force in different bracket-archwire angles and ligation methods over 1 month.

The results of the Bonferroni Post Hoc test (Table 2) showed that there was a statistically significant difference in the amount of the frictional force between the O-Ring and Fig-8 groups and SS-ligature wire and Fig-8 groups in NiTi archwires (P<0.001).

The mean values and standard deviation for kinetic friction over time for each ligation method for the SS archwires are shown in Table 3 and Figure 5. The results of the repeated measures ANOVA test showed that the interaction of time and ligation method was not statistically significant (F=0.201, P=0.975). However, time had a statistically significant effect on the amount of the frictional force (F=8.65, P<0.001), and the amount of frictional force decreased in all three ligation methods as time progressed.

The repeated measures ANOVA test showed that there was a statistically significant difference in the amount of the frictional force among different ligation methods (F=29.13, P<0.001). The mean frictional force was highest in the figure of 8 group and lowest in the SS-ligature wire group. Figure 5 shows the changes in the frictional force among different ligation methods over one month in SS archwires.

The results of the Bonferroni Post Hoc test (Table 4) showed that there was a statistically significant difference in the amount of the frictional force between the O-Ring and Fig-8 groups and SS-ligature wire and Fig-8 groups in SS wires (P<0.001).

DISCUSSION

The aim of this study was to assess the effect of different ligatures, including SS wire ligature and elastomeric modules, and different methods of ligations followed by a degradation process on the kinetic friction between SS brackets and two types of SS and NiTi wires with 0° and 10° bracket-wire angulations. As orthodontic tooth movement occurs, the frictional force generated in the bracket-wire-ligature assembly confronts the orthodontic force, which necessitates exerting more force to overcome the friction that might cause loss of anchorage and increase the risk of tooth root resorption. According to the literature, classical friction is generated when there is only a bracket-wire interface; however, with the addition of ligature, “binding” creates a type of friction that is more complex than classical friction [1-3]. During orthodontic tooth movement, a constant alteration occurs between the kinetic and static friction, and it is not like a smooth translation. In other words, the orthodontic tooth movement occurs in a stepwise, but not a continuous manner [32]. Therefore, both friction types have been considered important and should be evaluated in the studies.

As aforementioned, the authors found a decreasing pattern in all three types of ligations. A study by Edwards et al. [33] evaluating the effect of degradation of elastomeric modules on static friction showed a similar result as ours. They found a decrease in the static friction over time in elastic modules stored in artificial saliva. In another study by Dowling et al. [34], they observed both decrease, increase, and no change in frictional resistance over time in different groups. The issue was that the tests were conducted in the absence of natural or artificial saliva, which might have affected the results. Bortoly et al. [35] attributed the decrease in the frictional resistance to the loss of tensile strength subsequent to the degradation of elastomeric modules in the simulated oral environment rather than surface characteristics. However, other studies consider the surface structure of ligatures more efficacious [33].

These observations prevent us from attributing the changes in the friction only to the degradation process of elastomeric modules. Though, it is possible that the friction results from a combination of different factors, including orthodontic material (e.g., bracket, archwire, ligation module) structure and surface characteristics, oral environment factors, and contacts made from the bracket-wire-ligature assembly affecting at different levels in the lifespan of an elastomeric module. On the other hand, stress release of SS wire ligatures over time and their loosening might be an important factor in friction decrease in this group.

The results show that regardless of wire type and the bracket-wire angulation, the figure of 8 ligations created the most friction compared to O-ring and SS wire ligations. Similar results were obtained by Edwards et al. [26] and Voudouris et al. [36]. According to Khambay et al. [27] and Bazakidou et al. [37], SS wire ligatures generated the lowest friction among different ligatures. These results could be attributed to the increased surface contact of figure of 8 elastomeric ties with the archwire, compared to other groups. Another contributing factor could be the greater overall tightness associated with figure-of-8 ligations

Table 3: Mean values ± standard deviations of kinetic friction (N) over time for each group of stainless steel wires

Ligation Method	Baseline	Day1	Week1	Week4
O-ring	6.47±0.72	6.45±0.22	6.36±0.7	5.96±0.74
Figure of 8	7.27±0.3	7.31±0.31	7.18±0.52	6.79±0.51
Stainless steel ligature	6.38±0.4	6.38±0.16	6.24±0.2	5.61±1.03

Table 4: The results of the Bonferroni Post Hoc test for different ligation methods in Stainless steel wires

Group (I)	(J)	Mean difference (I-J)	95% Confidence interval	P
O-ring	**Figure of 8**	-0.82	(-1.18;-0.47)	<0.001
	Stainless steel ligature	0.1608	(-0.19;0.51)	0.767
Figure of 8	**Stainless steel ligature**	0.98	(0.63;1.34)	<0.001

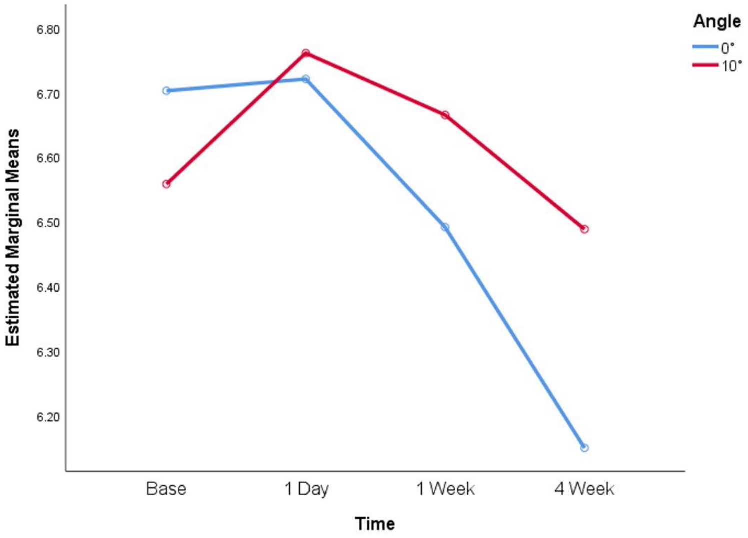

Fig. 3: The kinetic friction generated in nickel titanium archwire groups at different angles

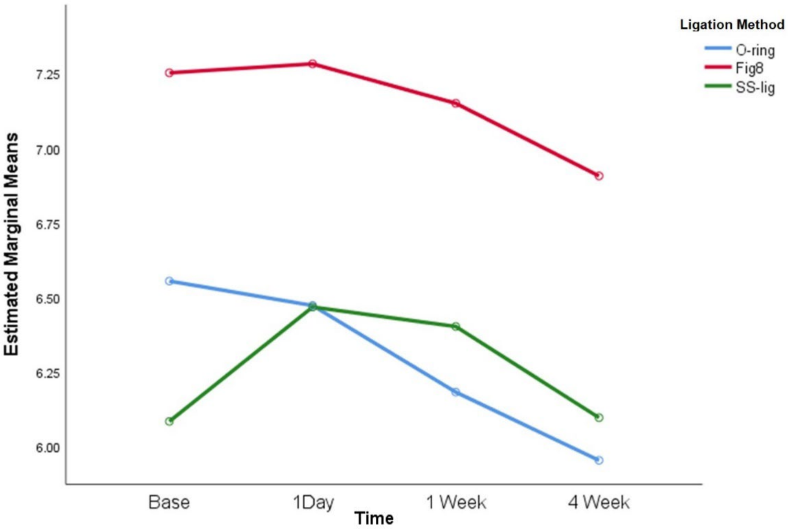

Fig. 4: The kinetic friction generated in nickel titanium archwire groups in different ligation methods

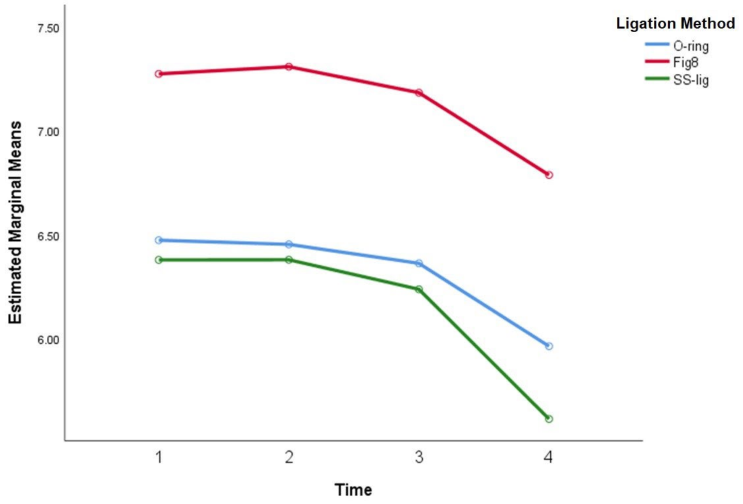

Fig. 5: The kinetic friction generated in Stainless steel archwire groups in different ligation methods

in comparison to alternative ligation methods, such as conventional O-ring ligation.

Some of the studies in the literature also did a comparison of frictional forces between different archwire materials. Tselepis et al. [32] and Peterson et al. [38] showed that the frictional force did not differ between NiTi and SS archwires. However, other studies have stated that there were significant differences in the created friction among assemblies containing NiTi and SS wires [9,10,13,39].

The reason for these controversies could be due to differences in the NiTi and SS wires made by various manufacturers in terms of surface and structural characteristics which were used in each different study. Also, it might be possible that the binding resulting from ligature insertion might have masked the real effect of wire type on the friction. Additionally, there are significant variations among the previous studies, which may cause considerably different results.

To examine the effect of bracket-wire angle, the authors compared the groups with the same wire and ligation type, but with different angulations. The results showed that the bracket-wire angle did not affect the kinetic friction.

The authors' results showed the neutral effect of bracket-wire angle alteration on kinetic friction. A study by Samorodnitzky-Naveh et al. [29] evaluated the impact of a specific coating of NiTi wires on both static and kinetic friction coefficients and showed that by increasing the angle from 2˚ to 3.8˚ and from 3.8˚ to 5˚ in uncoated wires, the kinetic friction coefficient decreased. In other studies by Tselepis et al. [32] and Jang et al. [28], it was stated that the higher bracket wire angulations increased the kinetic friction. The reason for these controversies might be because the angle alteration impacts the static and kinetic coefficient at different levels. Furthermore, there are significant methodological variations in study settings that make it hard to compare the results, like different friction simulation settings (e.g., using one or couple brackets to simulate second-order bend, the differences in designing paths to mimic archwire movement, etc.), the materials used from different manufacturers which might have different surface and structural characteristics and the machine used to record friction. Another reason for these controversies might be the dimension of NiTi wires used in this study, which creates a noticeable amount of wire play in the bracket slot and helps the wires to move more freely, not engaging the bracket's internal walls. These results might be different with using thicker wires.

The strength of the authors' study was that bracket-wire angle and ligation method were examined with one apparatus. Therefore, the condition for each group was the same and consistent in different ligation methods and angulations, which helped to obtain reliable results. The limitation of this study was that the complete simulation of the oral environment, such as tooth translation in the bone as a living element, the effect of adjacent teeth, muscular and occlusal force, was almost impossible. However, the authors tried to simulate the second-order bend, the degradation, and lubrication characteristics of saliva. The authors suggest that in future studies, new models closer to the oral environment or new instruments capable of examining friction created by bracket-wire-ligature assemblies in the mouth should be introduced.

Due to substantial methodological differences among the studies, such as testing apparatus models, saliva mimicking substances with different chemical compounds, orthodontic tooth movement simulations, etc., the authors were not able to compare the results freely. Also, the alteration in friction seemed to be multifactorial, and the authors could not attribute the changes in friction only to the angle, wire, and ligature type in general aspects. Therefore, the authors suggest that more standardized studies should be conducted for each of these three variables and minor attributes which belong to each of them in standard and constant conditions.

CONCLUSION

The authors found that the Figure of 8 ligation method created the most significant kinetic friction. However, there was no difference between SS wire and O-ring ligatures. These results are promising because ligating the bracket with an O-ring is more straightforward, safer, and less time-consuming than SS ligation, and there might be no need to use the SS ligation technique only to overcome friction and sliding difficulties.

The kinetic friction had decreasing patterns for all three ligation methods due to degradation processes of the elastomeric or ligature ties (O-ring, figure of 8, and SS wire ligatures).

The authors did not observe any effect of the bracket-wire angle on kinetic friction.

CONFLICT OF INTEREST STATEMENT

None declared.

ACKNOWLEDGEMENTS

This study was part of a thesis that received financial support from the Vice-Chancellor for Research, Tabriz University of Medical Sciences, Tabriz, Iran [grant number: 64392]. Tabriz University of Medical Sciences did not participate in the writing, editing, approval, or decision to publish the manuscript.

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