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Effect of Water Immersion on The Resistance to Sliding of Coated Orthodontic Archwires

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EFFECT OF WATER IMMERSION ON THE RESISTANCE TO SLIDING OF COATED ORTHODONTIC ARCHWIRES

JUN SIK KIM, D.D.S.,M.S.,Ph.D.

A Thesis Presented to the Faculty of the College of Dental Medicine of

Nova Southeastern University in Partial Fulfillment of the Requirements for the Degree

of

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I certify that I am the sole author of this thesis, and that any assistance I received in its preparation has been fully acknowledged and disclosed in the thesis. I have cited any sources from which I used ideas, data, or words, and labeled as quotations any directly quoted phrases or passages, as well as providing proper documentation and citations. This thesis was prepared by me, specifically for the M.Sc.D. degree and for this assignment.

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Abstract

EFFECT OF WATER IMMERSION ON RESISTANCE TO SLIDING OF COATED ORTHODONTIC ARCHWIRES

DEGREE DATE: DECEMBER 15, 2017

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Objectives: The objective of this *in vitro* study is to compare the resistance to sliding (RS) of coated and uncoated orthodontic archwires in ceramic brackets at various water-immersion times and bracket angulations. **Background:** Tooth-colored orthodontic systems have been developed to meet the patient's esthetic needs. Ceramic brackets and polymer-coated archwires have been shown to demonstrate higher RS than metal brackets and archwires in dry conditions. However, there is no study to address the RS of coated archwires depending on water-immersion times as in the oral cavity. Therefore, it is necessary to examine RS of coated archwires sliding in ceramic brackets up to 4 weeks of water immersion. **Methods**: Four groups of 0.019 x 0.025inch stainless-steel archwires: uncoated (group U), Parylene-coated (group P), epoxy-coated (group E), and Teflon-coated (group T) were used. They were immersed for 0 week (T0), 2 weeks (T2), and 4 weeks (T4), in distilled deionized water at 37°C. The RS was measured by sliding the archwires in 0.022inch-slot sapphire ceramic brackets in 0° or 3° bracket angulation.

Two general linear models were created to look for differences in RS with Tukey's HSD for all post-hoc comparisons. The integrity of the archwires was observed under microscope after the sliding test. **Results:** At 0° bracket angulation, there was no difference in RS between T0, T2, and T4 in groups T & U. In group P, RS at T4 was higher than RS at T0 & T2. In group E, RS at T2 was higher than RS at T0 & T4. At 3° bracket angulation, there was no difference in RS between T0, T2, and T4 in groups P & U. In groups T & E, RS at T4 was highest following RS at T0, and RS at T2 in descending order. All groups showed a higher RS at 3° bracket angulation than RS at 0° bracket angulation in all water immersion times, with exceptions of group T at T2 as no difference was noticed between two bracket angulations, and of group E at T2 as RS at 3° was lower than RS at 0°. Comparing to other groups, group P showed the highest RS in various bracket angulations and water-immersion times. At 0° bracket angulation, group T showed less percentage of coating delamination than the other groups after sliding test. At 3° bracket angulation, all archwires of all groups showed similar coating delamination after sliding test. **Conclusions:** Resistance to sliding was changed when coated archwires were immersed in water for periods of time. Among the independent variables, surface coating and bracket angulation played a major role in the resistance to sliding.

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Chapter 1: INTRODUCTION

1.1. The demand for esthetic appliances

There has been a change in the demographics of orthodontic patients in the USA and Canada. According to "The Economics of Orthodontics" survey by the American Association of Orthodontists, the number of adult orthodontic patients increased 16 percent from 2012 to 2014, resulting in a total 1,460,000 adult patients per year. The survey estimated that 27 percent of orthodontic patients in the U.S. and Canada are adults.[1]

The esthetic demand of adult orthodontic patients is different from that of juvenile patients.[2] Among adult orthodontic patients with a mean age of 22 years, 20.4% had complaints about unaesthetic smiles with metal braces.[3] Considering this kind of complaint and the increasing number of adult orthodontic patients, esthetic appliances such as tooth-colored or translucent archwires and brackets were developed to meet adult patient's esthetic demands.[4] With their tooth-like colors, these esthetic appliances were well received by patients. A recent survey showed that polymer-coated archwires, and sapphire ceramic brackets were in patients' top choices to replace conventional metal brackets and metal archwires.[5]

1.2. Coating materials

There are several materials used in coating orthodontic archwires, such as Parylene, epoxy resin, and Teflon.[6] Recently, Poly-paraxylylene, known as Parylene, was introduced to the coating industry. Parylene is the trade name for a variety of chemical vapor deposited poly-para-xylylene polymers. Among them, Parylene C is the most popular due to its combination of barrier properties, cost, and other processing advantages.[7] Parylene has various beneficial properties such as excellent thermal stability, chemical/moisture resistance, and low coefficient of friction.[8] Consequently, Parylene coatings have been applied to various fields, including hydrophobic coating for biomedical hose, implantable medical devices, corrosion protection for metallic surfaces, and reduction of friction for guiding catheters.[9]

Epoxy resin is the most common material for coating.[4] Epoxies are thermoset polymers having one or more active epoxide group. Epoxy polymers are used as protective coatings for appliances, encapsulation of electrical instruments, and dental bonding materials for its excellent chemical resistance, adhesion, durability at high and low temperatures, good electrical resistance, mechanical properties (high strength and toughness), and low shrinkage.[10,11]

Polytetrafluoroethylene (PTFE) is a synthetic fluoropolymer of tetrafluoroethylene. Teflon is the best-known brand name of PTFE-based formulas by Chemours.[12] Teflon have been applied to pacemakers, prosthetic joints, and bone replacements for its chemical inertness, low friction, anti-wear, and sealing performances.[13-15]

1.3. Resistance to sliding in orthodontics

The resistance to sliding (RS) is defined as the resistance to motion when a solid object moves tangentially against another.[16] For optimal orthodontic tooth movements, appropriate forces should be used to move teeth efficiently and accurately without damaging the teeth and their surrounding tissues.[17] However, 12-60% of the applied force in orthodontic treatment is lost to RS.[18] Two major orthodontic tooth movements such as sliding mechanics and closing loop mechanics demand different amounts of RS: sliding mechanics needs low RS and closing-loop mechanics needs high RS.[19] RS can change the orthodontic movements as 20% difference in RS with countervailing moments has been shown to bring opposite movements in crowns and roots.[18] Therefore, RS should be considered in a biomechanical design for orthodontic tooth movements along the archwires.[20]

1.4. Factors influencing RS in the present study

Water comprises 99.5% of the saliva in oral cavity.[21] It has been shown to change surface properties, such as elastic modulus, hardness, and tensile strength, of epoxy resin, a coating material used in coated archwires.[22] According to the Derjaguin-Müller-Toporov (DMT) model, RS is inversely proportional to the Young's modulus of contact surfaces.[23] It is possible that water can affect RS, lubrication, and wear characteristic of coated archwires when used clinically in the humid oral cavity. Recently, there have been several *in vivo* studies on the tribological properties of coated orthodontic archwires.[24-26] After 1 month oral exposure, coated archwires have shown increases in surface roughness and deterioration.[24] Teflon-coated archwires showed a decrease in bending strength when compared to uncoated controls after oral exposure for 4 weeks.[25] The increase in RS of epoxy-coated nickel titanium archwires was noted after 1 month of clinical use.[26]

The RS is composed of friction, binding, and notching depending on the active (high angulation) or passive (low angulation) configurations between brackets and archwires. In the passive configuration, when the archwire does not contact the mesial and distal edges of the bracket slot, only classic friction contributes to sliding resistance.[27] Classic "friction" is calculated as the normal force applied by ligation multiplied by the coefficient of friction, which is determined by the surface natures of brackets and archwire materials.[28] In the active configuration, when the archwire contacts the edges of the slot, "binding" begins to contribute to RS. The second-order angle (θ) at which the archwire first contacts both upper and lower edges of the opposing slot walls is called the critical contact angle for binding (θc).[27] At greater θ values, the bracket may physically deform the archwire, thus adding a physical "notching" component to the elastic binding and classic friction components of RS.[29] Research has shown that θc was below 2.0° for 0.019x0.025inch Stainless Steel (SS) archwire in a 0.022inch bracket slot.[27]

Among many factors influencing RS, surface properties of contacting materials are closely related to RS.[30] From an orthodontic point of view, Teflon is an esthetic material with excellent chemical inertia and low coefficient of friction. However, its poor durability renders it unfavorable as the best esthetic coating for archwires.[31] Parylene exhibits good mechanical properties, such as elasticity, high strength, low friction, good durability and low permeability to water, for orthodontic wire coating.[32,33] The coatings of esthetic archwires have been shown to affect the friction differently *in vitro*. Teflon coating decreased friction, but Parylene coating increased friction.[31,34]

Also, mechanical characteristics of archwire such as roughness, hardness, and wire stiffness influenced the RS of archwire.[18] Ryu *et al.* [35] reported 3 kinds of coated archwire (silver platinum and polymer coated NiTi Natural P, epoxy resin coated Orthoforce Ultraesthetic TM, and Teflon coated Perfect) showed different load-deflection properties. If base wires of experimental coated archwires were not same, it could lead to different RS due to different normal force of binding with nonparallel bracket-archwire situations.

1.5. Importance of Study

Since orthodontic coated archwires are utilized in the humid oral cavity, it is important to know whether coated archwires perform differently or not when they are immersed in water up to 4 weeks. To date, there is no study that addresses whether water immersion affects RS of archwires coated with Parylene, epoxy resin, and Teflon. Therefore, it is important to assess water immersion effects on these coated wires for optimal orthodontic practice. In this proposed study, the effects of water immersion on the RS of coated wires will be addressed. Results of this study can provide valuable information for the clinical use of coated archwires.

1.6. Purpose, Specific Aims and Hypotheses

1.6.1. Purpose

The purpose of this study was to compare the average resistance to sliding (ARS) and the maximum resistance to sliding (MRS) of various coated and uncoated archwires when sliding in ceramic sapphire brackets at various water immersion times and bracket angulations.

1.6.2. Specific Aims

1. To determine whether there is a difference in ARS between coated and uncoated archwires when sliding in sapphire brackets at various water immersion times and bracket angulations.
2. To determine whether there is a difference in MRS between coated and uncoated archwires when sliding in sapphire brackets at various water immersion times and bracket angulations.

1.6.3. Hypotheses

- ✓ **Null hypothesis:**

1. There is no difference in ARS between coated and uncoated archwires when sliding in sapphire brackets at various water immersion times and bracket angulations.
2. There is no difference in MRS between coated and uncoated archwires when sliding in sapphire brackets at various water immersion times and bracket angulations.

- ✓ **Alternate hypothesis:**

1. There is a difference in ARS between coated and uncoated archwires when sliding in sapphire brackets at various water immersion times and bracket angulations.
2. There is a difference in MRS between coated and uncoated archwires when sliding in sapphire brackets at various water immersion times and bracket angulations.

Chapter 2: Materials and Methods

2.1. Materials

2.1.1. Archwires

In this *in vitro* study, four groups of archwires were used: Parylene-coated SS archwires (group P) (n=30), epoxy-coated SS archwires (group E) (n=30), Teflon-coated SS archwires (group T) (n=30), and uncoated SS archwires (group U) (n=30). The archwires were listed below:

Group P: Dany aesthetic silver archwires (DANY BMT, Gyeonggi, Korea)

Group E: Ultraeshetic archwires (G&H, Indiana, USA)

Group T: Perfect archwires (Hubit, Gyeonggi, Korea)

Group U: Hubit uncoated archwires (Hubit, Gyeonggi, Korea)

The archwires were in the size of 0.019 x0.025 inches used clinically for sliding mechanics.[36]

The archwires were equally divided into three water immersion times: 0 week (T0) of water immersion (n=10), 2 weeks (T2) of water immersion (n=10), and 4 weeks (T4) of water immersion (n=10). In each water immersion time, the archwires were further divided into 2 bracket angulations: 0° bracket angulation (n=5) and 3° bracket angulation (n=5) (Figure 1).

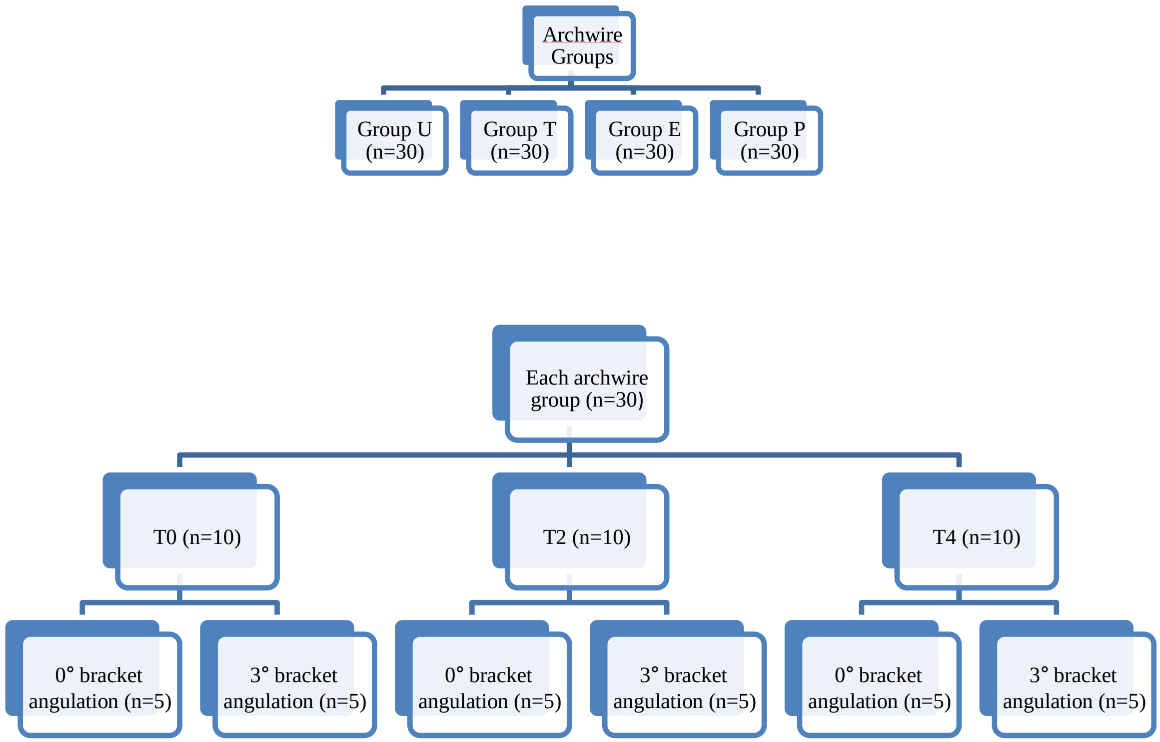

Figure 1. Grouping in experimental design

2.1.2. Brackets

Esthetic sapphire ceramic brackets, Radiance (American Orthodontics, Wisconsin, USA) of 0.022 inches slot (-7^{o} torque, and 0^{o} angulation for upper premolars) were used for all experiments.[4]

2.2. Methods

2.2.1. RS test

RS of coated and uncoated archwires when sliding in sapphire brackets at various water immersion times and bracket angulations was determined as ARS and MRS. Segments of the archwires (5 cm) were stored in distilled deionized (D.D.) water at 37^{o} C for T0, T2, and T4 (Figure 2).

a b

Figure 2. Archwires were immersed in D.D. water (a) and stored in an incubator at 37^{o}C (b)

The sliding of archwires in brackets was performed on a customized bracket-wire-holder assembly. The assembly is composed of an aluminum door hinges (Barton Kramer Inc. Miami, FL, USA) (0.25x1.31x5.19 inch) on which three brackets were bonded (Figure 3). The first and the third brackets were bonded in a fashion that the slots were aligned in a straight line. To access RS, the angle between the brackets and archwires will be fixed at 0° for the measurements of classic friction only and at 3° for the measurements of classic friction, binding and notching in this study. For the measurements of RS at 0° bracket angulation, the middle bracket was positioned so that its slot was aligned in a straight line with the slots of two neighboring brackets (Figure 3a). For the measurements of RS at 3° bracket angulation, the slot of the middle bracket was positioned 3° to the slots of neighboring brackets (Figure 3b). Each bracket angulation was tested by using a straight or 3° preformed 0.021 x 0.025inch SS wire (Figure 3). The distance between the centers of the brackets was always 8.0 mm.

An archwire was tied to the brackets with elastomeric modules (colored ligatures, American Orthodontics) to ensure consistent normal force of ligation.[26] The assembly was mounted on the universal testing machine (Instron 8841; Instron Corp., MA, USA) (Figure 4a). The archwire was pulled for a distance of 5 mm at a crosshead speed of 5 mm/min and with force range of up to 500 N by a loading weight of 100g (Figure 4b). The ARS and MRS were recorded for further statistical analysis. Each test was repeated five times with a new archwire. All tests were performed in wet condition maintained by spraying D.D. water onto the archwires and brackets.

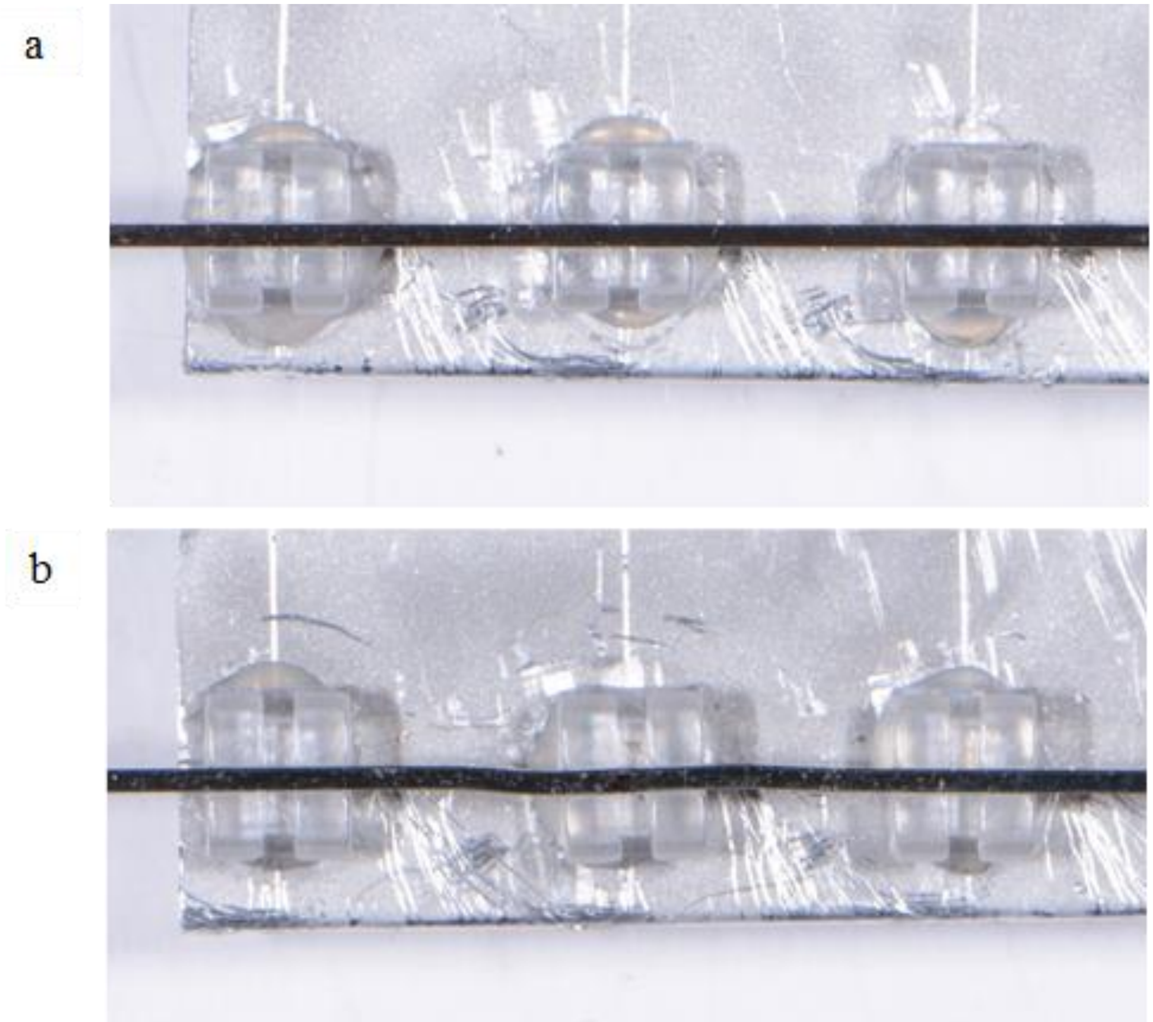

Figure 3. Bracket alignment. (a) 0° bracket angulation. (b) 3° bracket angulation

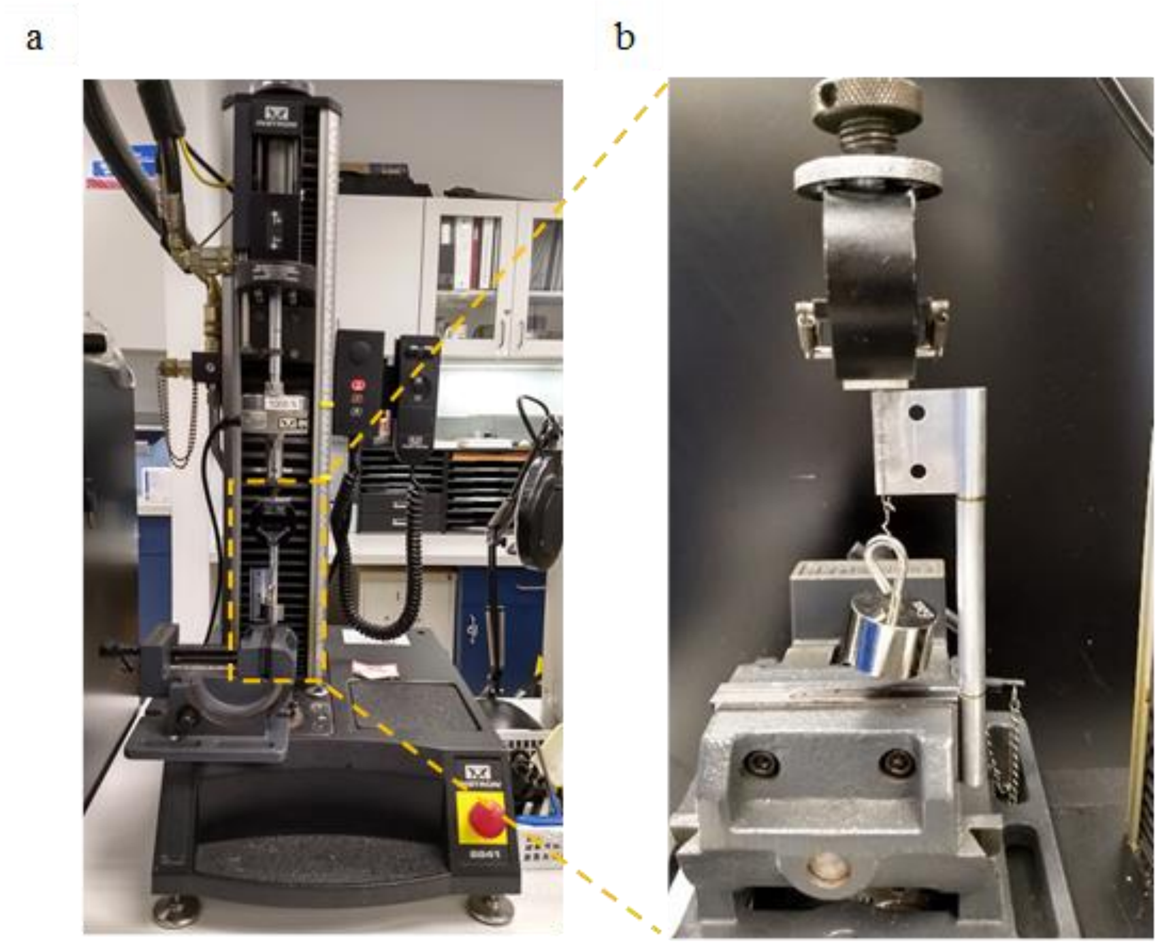

Figure 4. Resistance to sliding testing machine. (a) force measuring equipment. (b) bracket-wire-holder assembly

2.2.2. Surface morphology analysis

The surface morphology of archwires was photographed under a stereo microscope (SZX7 stereo microscope; Olympus Corp., Tokyo, Japan) at 10X magnification before and after the sliding test (Figure 5). The integrity of all archwires was determined by the delamination of archwire coating.

Figure 5. A stereo microscope

2.2.3. Variables evaluated

✓ **Independent variables**

1. Water immersion time: the archwires were immersed in D.D. water for 0 week (T0), 2 weeks (T2), and 4 weeks (T4).
2. Angle between archwire and bracket slot: 0°, and 3 ° bracket angulations were used for recording RS.
3. Archwire groups: Parylene-coated SS archwires (group P); epoxy-coated SS archwires (group E); Teflon-coated SS archwires (group T); and uncoated SS archwires (group U).

✓ **Dependent variables**

1. The average resistance to sliding (ARS): calculated by averaging the force while the archwire moved 1 to 5 mm.
2. The maximum resistance to sliding (MRS): calculated by measuring the maximum force during test.

2.3 Statistical analysis

Descriptive statistics were calculated for all study variables. This included the mean and standard deviation for continuous measures, counts and percentages for categorical variables.

Two general linear models were created to look for differences in MRS and ARS between the experimental groups. The fixed factors were water immersion time (T0, T2, T4), bracket angulation (0°, 3°), and archwire group (Group P, Group E, group T, group

U). The interaction effect was water immersion time x bracket angulation x archwire group.

The following linear model assumptions were checked and adjusted including: (1) the residuals are independent, (2) the residuals are normally distributed, (3) the residuals have a mean of 0 at all values of X, and (4) the residuals have constant variance.

Tukey's HSD was employed for all post-hoc comparisons. Effect size estimates including omega squared, with 95% confidence intervals, were also reported. The statistical package R 3.2.2 was used to create and test the models. Statistical significance was found at $p < 0.05$.

2.4. IRB Approval

IRB approval was not required for this study

2.5. Ethical Issues

No potential ethical issues could be identified as part of this research study.

2.6. Grant

This study was funded by a Health Professions Division grant at Nova Southeastern University (Grant No.335999).

Chapter 3: Results

3.1. ARS

There were differences in ARS between experimental groups when archwires slid in sapphire brackets at various water immersion times and bracket angulations.

3.1.1. Descriptive statistics of ARS for each archwire group at various water immersion times and bracket angulations

ARS was used to measure the kinetic resistance to sliding of archwires. The descriptive statistics of ARS for each archwire group at various water immersion times and bracket angulations were listed in Table 1. Further explanations were described in the section of statistical analysis.

Table 1. Descriptive statistics of ARS

Water immersion	Bracket angulation	Archwire group	N	Mean(gf)	SD	Min	Max
T0	0°	P	5	549.69	68.76	478.92	629.86
	0°	E	5	115.22	31.35	81.00	150.47
	0°	T	5	116.99	47.93	70.12	194.72
	0°	U	5	166.12	79.43	46.21	269.11
	3°	P	5	1159.94	116.79	1044.93	1355.84
	3°	E	5	435.25	85.60	336.53	563.40
	3°	T	5	565.75	141.60	383.58	742.75
	3°	U	5	521.90	142.84	353.45	700.38
T2	0°	P	5	335.98	123.00	169.31	465.79
	0°	E	5	224.25	31.96	183.67	258.31
	0°	T	5	203.90	101.44	136.43	382.24
	0°	U	5	196.91	76.65	84.44	298.90
	3°	P	5	1208.20	140.32	1048.28	1361.00
	3°	E	5	145.33	44.29	80.39	202.74
	3°	T	5	109.24	73.35	11.00	191.40
	3°	U	5	574.44	149.61	394.73	777.06
T4	0°	P	5	828.78	119.04	714.12	998.13
	0°	E	5	118.85	41.04	66.19	170.95
	0°	T	5	159.13	64.48	104.89	265.47
	0°	U	5	111.51	39.70	73.02	177.63
	3°	P	5	1167.38	123.45	1070.87	1376.83
	3°	E	5	445.64	61.63	387.14	524.13
	3°	T	5	1220.93	231.58	972.52	1567.41
	3°	U	5	537.47	274.82	115.78	855.07

3.1.2 Statistical analysis of ARS for each archwire group at various water immersion times and bracket angulations

A three-way ANOVA was run on a sample of 120 observations to examine the effect of water immersion times (T0, T2, T4), bracket angulations (0°, 3°), and archwire groups (P, E, T, U) on ARS. The results with effect size estimates were found in Table 2. There was a significant three-way interaction, F (23, 96) = 53.98, $p < 0.001$. Resulting effect size estimates (omega-squared) indicated that bracket angulations (ω^2=0.28) and archwire groups (ω^2=0.38) had the biggest effect on ARS with water immersion time (ω^2=0.04) and the interactions (ω^2=0.02~0.10) between three independent variables showing significant effects too.

Table 2. Three-way ANOVA Table of ARS

	SS	df	MS	F value	Pr(>F)	ω^2
Water immersion	802540	2	401270.15	29.43	<0.001*	0.04
Bracket angulation	5133852	1	5133851.50	376.51	< 0.001*	0.28
Archwire group	6992382	3	2330794.10	170.94	< 0.001*	0.38
Water immersion: Bracket angulation	368485	2	184242.45	13.51	<0.001*	0.02
Water immersion: Archwire group	1005190	6	167531.72	12.29	<0.001*	0.05
Bracket angulation: Archwire group	689018	3	229672.70	16.84	<0.001*	0.04
Water immersion: Bracket angulation: Archwire group	1937524	6	322920.65	23.68	<0.001*	0.10
Residuals	1309010	96	13635.52			
Total	18238002					

Residual standard error: 116.8 on 96 degrees of freedom
Multiple R-squared: 0.9282, Adjusted R-squared: 0.911
F-statistic: 53.98 on 23 and 96 DF, p-value: < 2.2e-16
*: Statistically significant

3.1.3. ARS changes related to water immersion times and bracket angulations in each archwire group

The Tukey pairwise comparisons of ARS related to water immersion times and bracket angulations in each archwire group were shown in Table 3. The Summary of ARS changes related to bracket angulations and water immersion times in each archwire group was listed in Table 4. Archwire groups showed distinct patterns in the timely changes of ARS with water immersion in Table 3 and 4. They also showed distinct relationships of ARS between at 0° and 3° bracket angulations at each time point in Table 3 and 4.

In group P, ARS at T4 (878.78 ± 119.04gf) was significantly higher than those at T0 (549.69 ± 68.76gf) and T2 (335.98 ± 123.00gf) with no difference between them at 0° bracket angulation. At 3° bracket angulation, there was no significant difference in ARS between at T0, T2, and T4 (T0: 1159.94 ± 116.79gf, T2: 1208.20 ± 140.32gf, T4: 1167.38 ± 123.45gf). ARS at 3° bracket angulation (T0: 1159.94 ± 116.79gf, T2: 1208.20 ± 140.32gf, T4: 1167.38 ± 123.45gf) was significantly higher than that at 0° bracket angulation (T0: 549.69 ± 68.76gf, T2: 335.98 ± 123.00gf, T4: 878.78 ± 119.04gf) at T0, T2, and T4.

In group E, ARS at T2 (T2: 224.35 ± 31.96gf) was significantly higher than those at T0 and T4 (T0: 115.22 ± 31.35gf, T4: 118.85 ± 41.04gf) with no difference between them at 0° bracket angulation. At 3° bracket angulation, ARS at T4 (T4: 445.64 ± 61.63gf) was the highest, followed by that at T0 (T0: 435.25 ± 85.60gf) and T2 (T2: 145.33 ± 44.29gf) in a descending order. ARS at 3° bracket angulation (T0: 435.25 ± 85.60gf, T4: 445.64 ± 61.63gf) was significantly higher than that at 0° bracket angulation

(T0: 115.22 ± 31.35gf, T4: 118.85 ± 41.04gf) at T0 and T4. However, ARS at 3° bracket angulation (T2: 145.33 ± 44.29gf) was significantly lower than that at 0° bracket angulation (T2: 224.35 ± 31.96gf) at T2.

In group T, there was no significant difference in ARS (T0: 116.99 ± 47.93gf, T2: 203.90 ± 101.44gf, T4: 159.13 ± 64.48gf) between at T0, T2, and T4 at 0° bracket angulation. At 3° bracket angulation, ARS at T4 (T4: 1220.93 ± 231.58gf) was the highest, followed by that at T0 (T0: 565.75 ± 141.60gf), and T2 (T2: 109.24 ± 73.35gf) in descending order. ARS at 3° bracket angulation (T0: 565.75 ± 141.60gf, T4: 1220.93 ± 231.58gf) was significantly higher than that at 0° bracket angulation (T0: 116.99 ± 47.93gf, T4: 159.13 ± 64.48gf) at T0 and T4. However, there was no significant difference in ARS between at 0° (T2: 203.90 ± 101.44gf) and 3° bracket angulation (T2: 109.24 ± 73.35gf) at T2.

In group U, there was no significant difference in ARS between at T0, T2, and T4 at 0° or 3° bracket angulations. ARS at 3° bracket angulation (T0: 521.90 ± 142.84gf, T2: 574.44 ± 149.61gf, T4: 537.47 ± 274.82gf) was significantly higher than that at 0° bracket angulation (T0: 166.12 ± 79.43gf, T2: 196.91 ± 76.65gf, T4: 111.51 ± 39.70gf) at T0, T2, and T4.

Table 3. Pairwise comparisons of ARS with a Tukey adjustment based on archwire group

Archwire group P

Water immersion	Bracket angulation	Mean (gf)	SE	Lower 95% CI	Upper 95% CI	Cluster*
T0	0°	549.69	52.22	446.03	653.35	a
T2	0°	335.98	52.22	232.32	439.64	a
T4	0°	828.78	52.22	725.12	932.44	b
T0	3°	1159.94	52.22	1056.28	1263.60	c
T2	3°	1208.20	52.22	1104.54	1311.86	c
T4	3°	1167.38	52.22	1063.72	1271.04	c

*Clusters not connected by the same letter are significantly different

Archwire group E

Water immersion	Bracket angulation	Mean (gf)	SE	Lower 95% CI	Upper 95% CI	Cluster*
T0	0°	115.22	52.22	11.56	218.88	a
T2	0°	224.25	52.22	120.59	327.91	ab
T4	0°	118.85	52.22	15.19	222.51	a
T0	3°	435.25	52.22	331.59	538.91	bc
T2	3°	145.33	52.22	41.67	248.99	a
T4	3°	445.64	52.22	341.98	549.30	c

*Clusters not connected by the same letter are significantly different

Archwire group T

Water immersion	Bracket angulation	Mean (gf)	SE	Lower 95% CI	Upper 95% CI	Clusters*
T0	0°	116.99	52.22	13.33	220.65	a
T2	0°	203.90	52.22	100.24	307.56	a
T4	0°	159.13	52.22	55.47	262.79	a
T0	3°	565.75	52.22	462.09	669.41	b
T2	3°	109.24	52.22	5.58	212.90	a
T4	3°	1220.93	52.22	1117.27	1324.59	c

*Clusters not connected by the same letter are significantly different

Archwire group U

Water immersion	Bracket angulation	Mean (gf)	SE	Lower 95% CI	Upper 95% CI	Clusters*
T0	0°	166.12	52.22	62.46	269.78	a
T2	0°	196.91	52.22	93.25	300.57	a
T4	0°	111.51	52.22	7.85	215.17	a
T0	3°	521.90	52.22	418.24	625.56	b
T2	3°	574.44	52.22	470.78	678.10	b
T4	3°	537.47	52.22	433.81	641.13	b

*Clusters not connected by the same letter are significantly different

Table 4. Summary of ARS changes related to water immersion times and bracket angulations in each archwire group

Archwire Group	0° bracket angulation	3° bracket angulation	Comparing 0° and 3° bracket angulation
P	T4>T0, T2	No difference between T0, T2, T4	3°>0° at T0, T2, T4
E	T2>T0, T4	T4>T0>T2	3°>0° at T0, T4 0°>3°at T2
T	No difference between T0, T2, T4	T4>T0>T2	3°>0° at T0, T4 No difference at T2
U	No difference between T0, T2, T4	No difference between T0, T2, T4	3°>0° at T0, T2, T4

3.1.4. ARS differences between archwire groups at various water immersion times and bracket angulations

The Tukey pairwise comparisons of ARS between arch wire groups at various water immersion times and different bracket angulations were found in Table 5. The summary of ARS differences between archwire groups at various water immersion times and bracket angulations was listed at Table 6. When compared to groups E, T, and U, group P showed the highest ARS at all conditions except at T2 at 0° bracket angulation in which there was no significant difference between all groups.

At T0, group P (0°: 549.69 ± 68.76gf, 3°: 1159.94 ± 116.79gf) showed significantly higher ARS than the other three archwire groups with no significant difference between group E (0°: 115.22 ± 31.35gf, 3°: 435.25 ± 85.60gf), T, (0°: 116.99 ± 47.93gf, 3°: 565.75 ± 141.60gf) and U (0°: 166.12 ± 79.43gf, 3°: 521.90 ± 142.84gf) at 0° or 3° bracket angulations (Figure 6).

At T2, there was no significant difference between all four groups (P: 335.98 ± 123.00gf, E: 224.25 ± 31.96gf, T: 203.90 ± 101.44gf, U: 196.91 ± 76.65gf) at 0° bracket angulation (Figure 7: left). However, Group P (1208.20 ± 140.32gf) showed the highest

ARS, followed by group U (574.44 ± 149.61gf), group E (145.33 ± 44.29gf), and group T (109.24 ± 73.35gf) with no difference between group T & E at 3° bracket angulation (Figure 7: right).

At T4, group P (828.78 ± 119.04gf) showed significantly higher ARS than the other archwire groups with no significant difference between group E (118.85 ± 41.04gf), T (159.13 ± 64.48gf), and U (111.51 ± 39.70gf) at 0° bracket angulation (Figure 8: left). At 3° bracket angulation, Group P (1167.38 ± 123.45gf) and T (1220.93 ± 231.58gf) showed significantly higher ARS than group E (445.64 ± 61.63gf) and U (537.47 ± 274.82gf) with no significant difference between group P & T and between group E & U at T4 (Figure 8: right).

Table 5. Pairwise comparisons of ARS with a Tukey adjustment based on water immersion time

Water immersion	**T0**					
Archwire group	Bracket angulation	Mean	SE	Lower 95% CI	Upper 95% CI	Cluster*
E	0°	115.22	52.22	11.56	218.88	a
T	0°	116.99	52.22	13.33	220.65	a
U	0°	166.12	52.22	62.46	269.78	a
E	3°	435.25	52.22	331.59	538.91	b
U	3°	521.90	52.22	418.24	625.56	b
P	0°	549.69	52.22	446.03	653.35	b
T	3°	565.75	52.22	462.09	669.41	b
P	3°	1159.94	52.22	1056.28	1263.60	c

- Clusters not connected by the same letter are significantly different

Water immersion	**T2**					
Archwire group	Bracket angulation	Mean	SE	Lower 95% CI	Upper 95% CI	Cluster*
T	3°	109.24	52.22	5.58	212.90	a
E	3°	145.33	52.22	41.67	248.99	a
U	0°	196.91	52.22	93.25	300.57	a
T	0°	203.90	52.22	100.24	307.56	a
E	0°	224.25	52.22	120.59	327.91	a
P	0°	335.98	52.22	232.32	439.64	a
U	3°	574.44	52.22	470.78	678.10	b
P	3°	1208.20	52.22	1104.54	1311.86	c

- Clusters not connected by the same letter are significantly different

Water immersion	**T4**					
Archwire group	Bracket angulation	Mean	SE	Lower 95% CI	Upper 95% CI	Cluster*
U	0°	111.51	52.22	7.85	215.17	a
E	0°	118.85	52.22	15.19	222.51	a
T	0°	159.13	52.22	55.47	262.79	a
E	3°	445.64	52.22	341.98	549.30	b
U	3°	537.47	52.22	433.81	641.13	b
P	0°	828.78	52.22	725.12	932.44	c
P	3°	1167.38	52.22	1063.72	1271.04	d
T	3°	1220.93	52.22	1117.27	1324.59	d

- Groups not connected by the same letter are significantly different

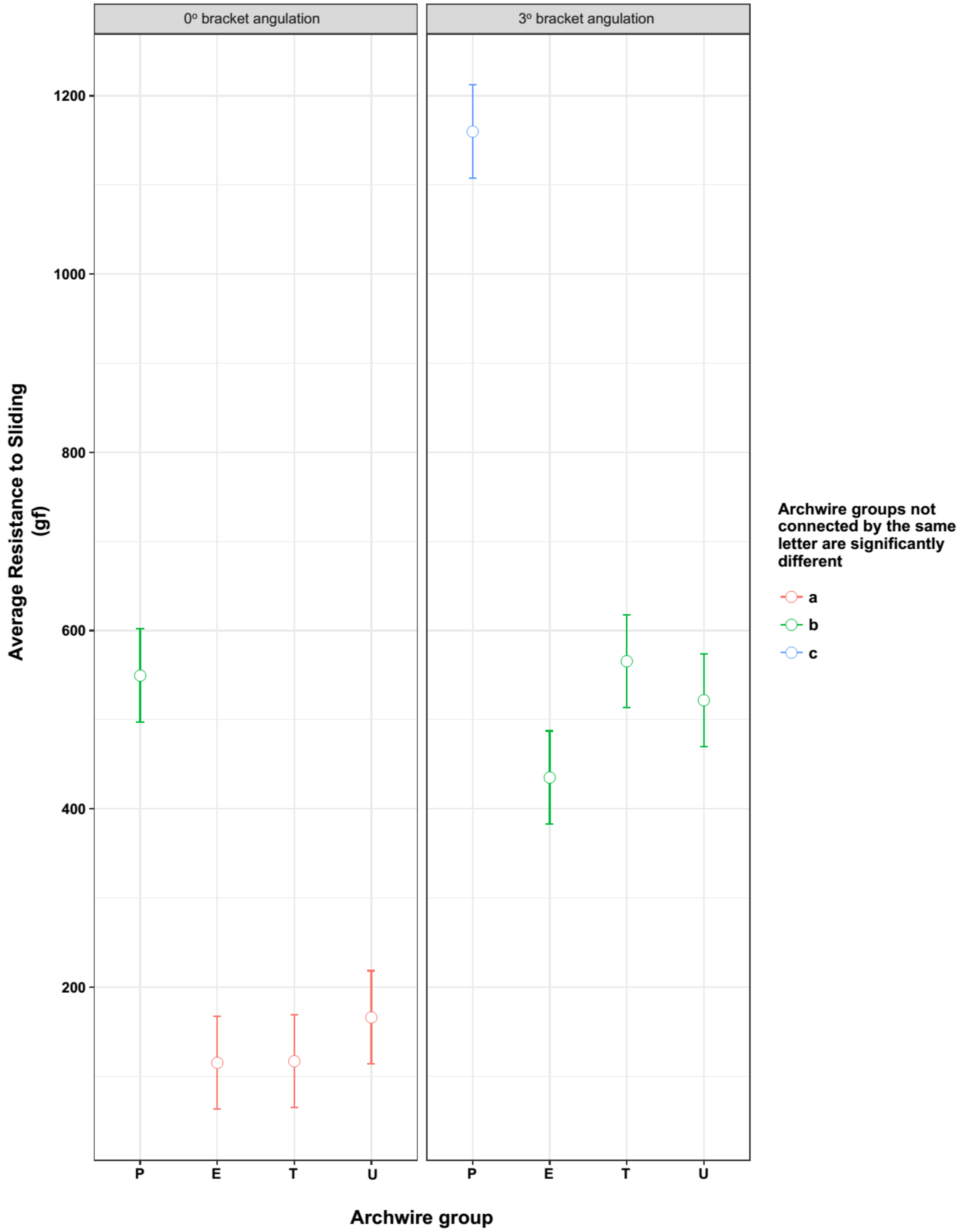

Figure 6. Least squares mean plot of ARS of each archwire group at T0 with standard error

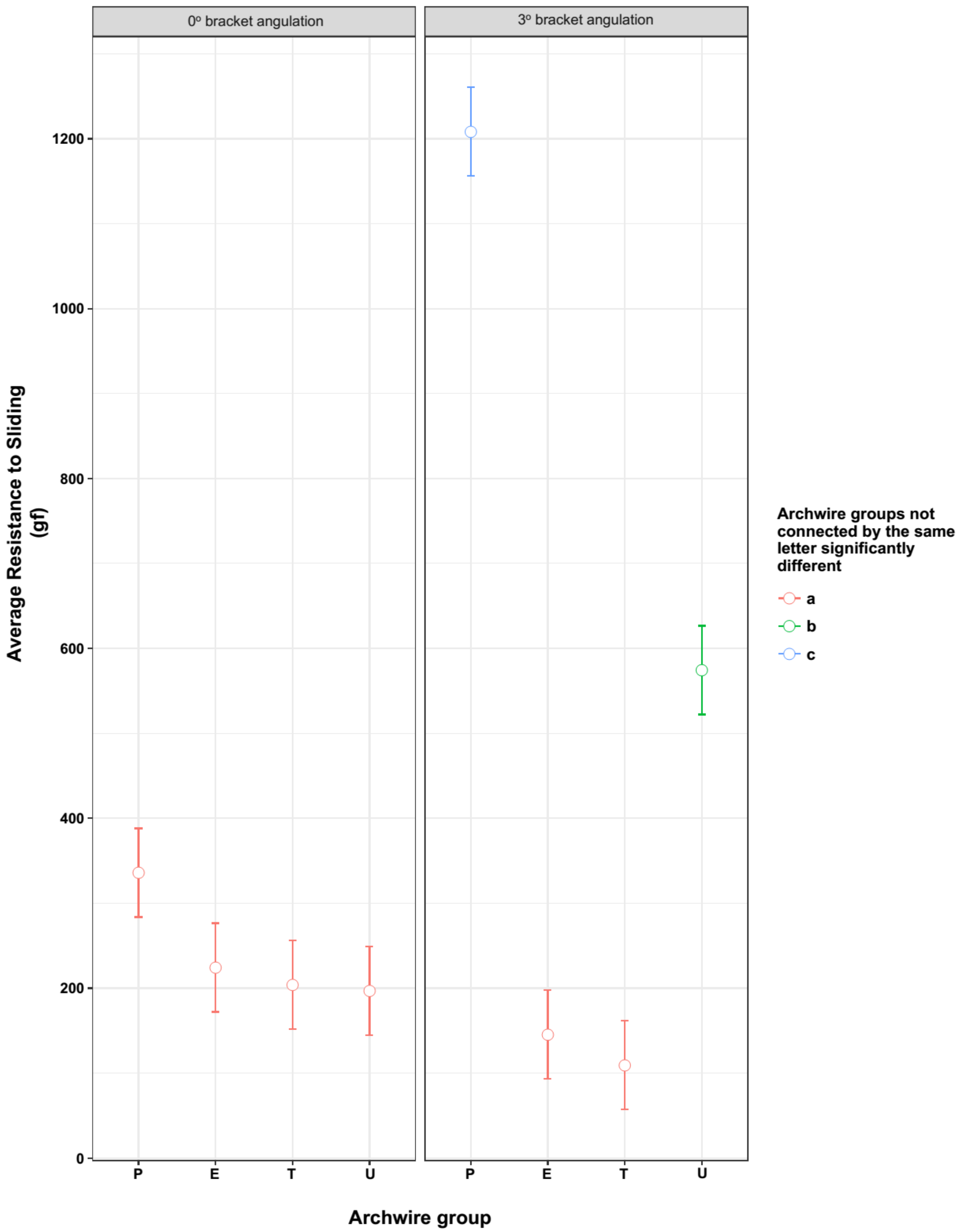

Figure 7. Least squares mean plot of ARS of each archwire group at T2 with standard error

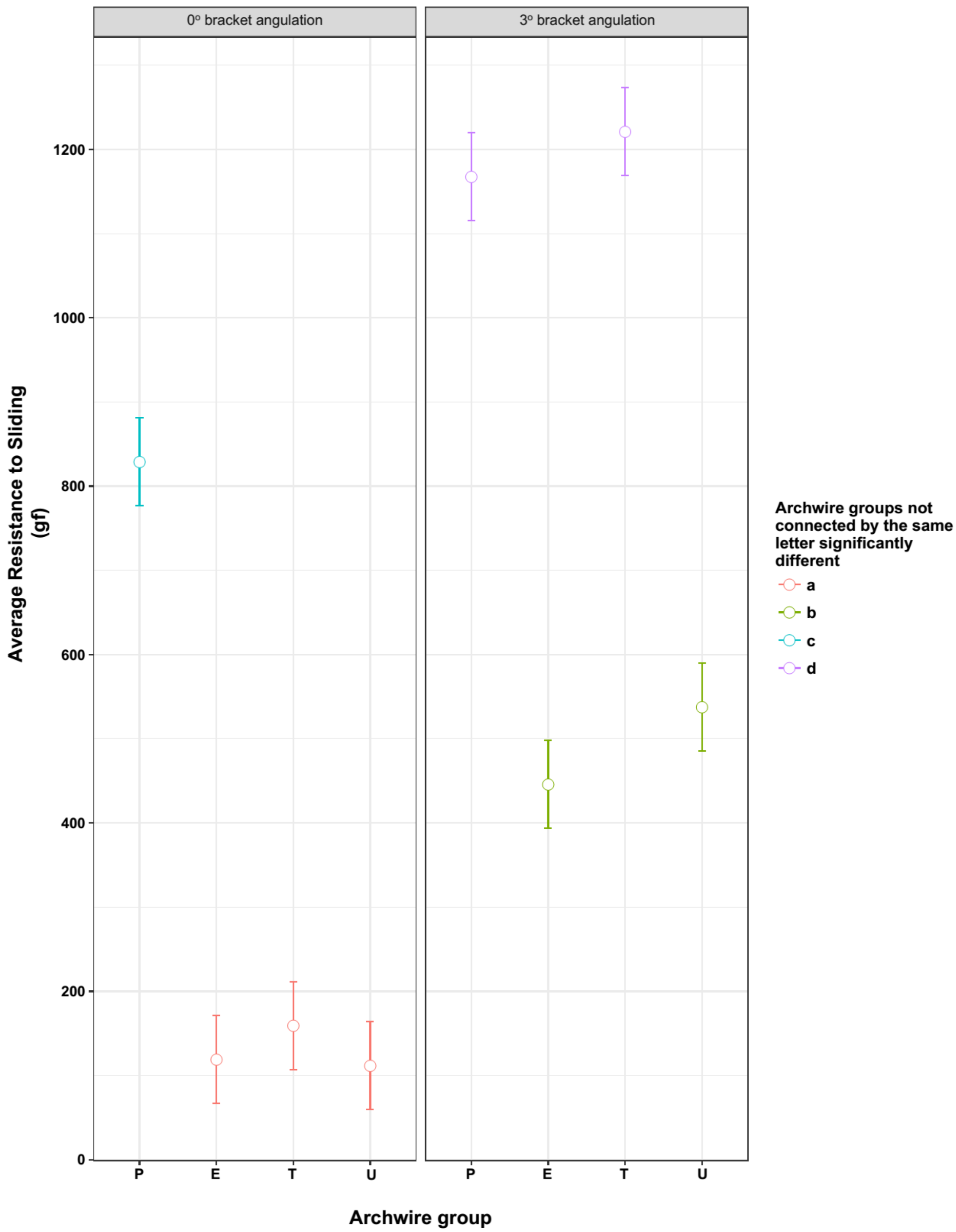

Figure 8. Least squares mean plot of ARS of each archwire group at T4 with standard error

Table 6. Summary of ARS differences between archwire groups at various water immersion times and bracket angulations

Water immersion time	0° bracket angulation	3° bracket angulation
T0	P> E, T, U	P> E, T, U
T2	No difference between Groups	P> U> T, E
T4	P> E, T, U	P, T> E, U

3.2 MRS

There were differences in MRS between experimental groups when archwires slid in sapphire brackets at various water immersion times and bracket angulations.

3.2.1 Descriptive statistics of MRS for each archwire group at various water immersion times and bracket angulations

MRS was used to measure the maximum resistance to sliding which needed to be overcome when archwires sliding. The descriptive statistics of MRS for each archwire group at various water immersion times and bracket angulations were listed in Table 7. Further explanations were described in the section of statistical analysis.

Table 7. Descriptive statistics for MRS

Water immersion	Bracket angulation	Archwire group	N	Mean (gf)	SD	Min	Max
T0	0°	P	5	760.22	151.03	633.70	952.80
	0°	E	5	204.24	34.48	168.40	255.70
	0°	T	5	181.82	40.09	143.90	248.30
	0°	U	5	302.18	77.01	181.20	394.50
	3°	P	5	1440.78	106.13	1341.20	1618.80
	3°	E	5	557.96	94.54	430.30	673.50
	3°	T	5	812.96	90.24	694.10	933.10
	3°	U	5	703.02	60.36	652.30	780.60
T2	0°	P	5	531.48	161.51	261.60	685.70
	0°	E	5	335.22	56.83	276.10	396.40
	0°	T	5	260.24	107.52	194.80	450.10
	0°	U	5	261.66	83.33	155.10	387.50
	3°	P	5	1496.74	140.87	1332.40	1669.10
	3°	E	5	235.30	42.82	183.30	298.30
	3°	T	5	210.00	25.44	185.00	240.90
	3°	U	5	691.28	147.99	553.60	901.40
T4	0°	P	5	1105.22	284.99	872.90	1454.50
	0°	E	5	193.32	25.89	163.80	218.50
	0°	T	5	244.08	88.83	170.10	398.60
	0°	U	5	175.82	39.62	146.10	245.40
	3°	P	5	1459.58	203.38	1280.20	1803.10
	3°	E	5	610.02	53.94	547.50	657.60
	3°	T	5	1446.94	220.31	1174.70	1763.90
	3°	U	5	700.36	201.89	390.90	946.50

3.2.2 Statistical analysis of MRS for each archwire group at various water immersion times and bracket angulations

A three-way ANOVA was run on a sample of 120 observations to examine the effect of water immersion times (T0, T2, T4), bracket angulations (0°, 3°), and archwire groups (P, E, T, U) on MRS. The results with effect size estimates were found in Table 8. There was a significant three-way interaction, F (23, 96) = 65.75, p < 0.001. Similar to the results in ARS, resulting effect size estimates (omega-squared) indicated that bracket angulation (ω^2=0.27) and archwire group (ω^2=0.42) had the biggest effect on MRS with water immersion time (ω^2=0.04) and the interactions (ω^2=0.02~0.09) between three independent variables showing significant effects too.

Table 8. Three-way ANOVA Table of MRS

	SS	df	MS	F value	Pr(>F)	ω^2
Water immersion	1144217.00	2	572108.49	36.09	<0.001*	0.04
Bracket angulation	7031165.20	1	7031165.23	443.50	< 0.001*	0.27
Archwire group	10883780.00	3	3627926.66	228.84	< 0.001*	0.42
Water immersion: Bracket angulation	506997.70	2	253498.83	15.99	<0.001*	0.02
Water immersion: Archwire group	1204304.60	6	200717.43	12.66	<0.001*	0.04
Bracket angulation: Archwire group	858930.60	3	286310.21	18.06	<0.001*	0.03
Water immersion: Bracket angulation: Archwire group	2346213.30	6	391035.55	24.67	<0.001*	0.09
Residuals	1521956.90	96	15853.72			
Total	25497565.30					

Residual standard error: 125.9 on 96 degrees of freedom
Multiple R-squared: 0.9403, Adjusted R-squared: 0.926
F-statistic: 65.75 on 23 and 96 DF, p-value: < 2.2e-16
*: Statistically significant

3.2.3 MRS changes related to water immersion times and bracket angulations in each archwire group

The Tukey pairwise comparisons of MRS related to bracket angulation and water immersion time in each archwire groups were shown in Table 9. The summary of MRS changes related to bracket angulations and water immersion times in each archwire group was listed in Table 10. Archwire groups showed distinct patterns in the timely changes of MRS with water immersion in Table 9 and 10. They also showed distinct relationship of MRS between 0° and 3° bracket angulations at each time point in Table 9 and 10.

In group P, MRS at T4 (1105.22 ± 284.99gf) was significantly higher than those at T0 (760.22 ± 151.03gf) and T2 (531.48 ± 161.51gf) with no significant difference between them at 0° bracket angulation. At 3° bracket angulation, there was no significant difference in MRS between at T0, T2, and T4 (T0: 1440.78 ± 106.13gf, T2: 1496.74 ± 140.87gf, T4: 1459.58 ± 203.38gf). MRS at 3° bracket angulation (T0: 1440.78 ± 106.13gf, T2: 1496.74 ± 140.87gf, T4: 1459.58 ± 203.38gf) was significantly higher than that at 0° bracket angulation (T0: 760.22 ± 151.03gf, T2: 531.48 ± 161.51gf, T4: 1105.22 ± 284.99gf) at T0, T2, and T4.

In group E, MRS at T2 (T2: 335.22 ± 56.83gf) was significantly higher than those at T0 and T4 (T0: 204.24 ± 34.48gf, T4: 193.32 ± 25.89gf) with no difference between them at 0° bracket angulation. At 3° bracket angulation, MRS at T4 (T4: 610.02 ± 53.94gf) was the highest, followed by that at T0 (T0: 557.96 ± 94.54gf), and T2 (T2: 235.30 ± 42.82gf). MRS at 3° bracket angulation (T0: 557.96 ± 94.54gf, T4: 610.02 ± 53.94gf) was significantly higher than that at 0° bracket angulation (T0: 204.24 ± 34.48gf, T4: 193.32 ± 25.89gf) at T0 and T4. However, MRS at 3° bracket angulation

(T2: 235.30 ± 42.82gf) was significantly lower than that at 0° bracket angulation (T2: 335.22 ± 56.83gf) at T2.

In group T, there was no significant difference in MRS between at T0, T2, and T4 (T0: 181.82 ± 40.09gf, T2: 210.00 ± 25.44gf, T4: 244.08 ± 88.83gf) at 0° bracket angulation. At 3° bracket angulation, MRS at T4 (T4: 1446.94 ± 220.31gf) was the highest, followed by at T0 (T0: 812.96 ± 90.24gf), and T2 (T2: 210.00 ± 25.44gf) in descending order. MRS at 3° bracket angulation (T0: 812.96 ± 90.24gf, T4: 1446.94 ± 220.31gf) was significantly higher than that at 0° bracket angulation (T0: 181.82 ± 40.09gf, T4: 244.08 ± 88.83gf) at T0 and T4. However, there was no significant difference in MRS between at 0° (T2: 260.24 ± 107.52gf) and 3° bracket angulation (T2: 210.00 ± 25.44gf) at T2.

In group U, there was no significant difference in MRS at various water immersion times and bracket angulations. MRS at 3° bracket angulation (T0: 703.02 ± 60.36gf, T2: 691.28 ± 147.99gf, T4: 700.36 ± 201.89gf) was significantly higher than that at 0° bracket angulation (T0: 302.18 ± 77.01gf, T2: 261.66 ± 83.33gf, T4: 175.82 ± 39.62gf) at T0, T2, and T4.

Table 9. Pairwise comparisons of MRS with a Tukey adjustment based on archwire group

Archwire group P

Water immersion	Bracket angulation	Mean (gf)	SE	Lower 95% CI	Upper 95% CI	Cluster*
T0	0°	760.22	56.31	648.45	871.99	a
T2	0°	531.48	56.31	419.71	643.25	a
T4	0°	1105.22	56.31	993.45	1216.99	b
T0	3°	1440.78	56.31	1329.01	1552.55	c
T2	3°	1496.74	56.31	1384.97	1608.51	c
T4	3°	1459.58	56.31	1347.81	1571.35	c

*Clusters not connected by the same letter are significantly different

Archwire group E

Water immersion	Bracket angulation	Mean (gf)	SE	Lower 95% CI	Upper 95% CI	Cluster*
T0	0°	204.24	56.31	92.47	316.01	a
T2	0°	335.22	56.31	223.45	446.99	ab
T4	0°	193.32	56.31	81.55	305.09	a
T0	3°	557.96	56.31	446.19	669.73	bc
T2	3°	235.30	56.31	123.53	347.07	a
T4	3°	610.02	56.31	498.25	721.79	c

*Clusters not connected by the same letter are significantly different

Archwire group T

Water immersion	Bracket angulation	Mean (gf)	SE	Lower 95% CI	Upper 95% CI	Cluster*
T0	0°	181.82	56.31	70.05	293.59	a
T2	0°	260.24	56.31	148.47	372.01	a
T4	0°	244.08	56.31	132.31	355.85	a
T0	3°	812.96	56.31	701.19	924.73	b
T2	3°	210.00	56.31	98.23	321.77	a
T4	3°	1446.94	56.31	1335.17	1558.71	c

*Clusters not connected by the same letter are significantly different

Archwire group U

Water immersion	Bracket angulation	Mean (gf)	SE	Lower 95% CI	Upper 95% CI	Cluster*
T0	0°	302.18	56.31	190.41	413.95	a
T2	0°	261.66	56.31	149.89	373.43	a
T4	0°	175.82	56.31	64.05	287.59	a
T0	3°	703.02	56.31	591.25	814.79	b
T2	3°	691.28	56.31	579.51	803.05	b
T4	3°	700.36	56.31	588.59	812.13	b

*Clusters not connected by the same letter are significantly different

Table 10. Summary of MRS changes related to water immersion times and bracket angulations in each archwire group

Archwire Group	0° bracket angulation	3° bracket angulation	Between 0° and 3° bracket angulation
P	T4>T0, T2	No difference between T0, T2, T4	3°>0° at T0, T2, T4
E	T2>T0, T4	T4>T0>T2	3°>0° at T0, T4 0°>3°at T2
T	No difference between T0, T2, T4	T4>T0>T2	3°>0° at T0, T4 No difference at T2
U	No difference between T0, T2, T4	No difference between T0, T2, T4	3°>0° at T0, T2, T4

3.2.4. MRS differences between archwire groups at various water immersion times and bracket angulations

The Tukey pairwise comparisons of MRS between arch wire groups at various water immersion times and bracket angulations were found in Table 11. The summary of MRS differences between archwire groups at various water immersion times and bracket angulations was listed at Table 12. When compared to groups E, T, and U, group P showed the highest MRS at all conditions

At T0, group P (0°: 760.22 ± 151.03gf, 3°: 1440.78 ± 106.13gf) showed significantly higher MRS than the other three archwire groups with no significant difference between group E (0°: 204.24 ± 34.48gf, 3°: 557.96 ± 94.54gf), T, (0°: 181.82 ± 40.09gf, 3°: 812.96 ± 90.24gf) and U (0°: 302.18 ± 77.01gf, 3°: 703.02 ± 60.36gf) at 0° and 3° bracket angulations (Figure 9).

At T2, Group P (531.48 ± 161.51gf) showed the highest MRS, followed by group E (335.22 ± 56.83gf) with group U (261.66 ± 83.33gf) & group T (260.24 ± 107.52gf) showing the lowest values at 0° bracket angulation. Group P (1496.74 ± 140.87gf) showed the highest MRS, followed by group U (691.28 ± 147.99gf) with group E (235.30

± 42.82gf) & group T (210.00 ± 25.44gf) showing the lowest values at 3° bracket angulation (Figure 10: right).

At T4, group P (1105.22 ± 284.99gf) showed significantly higher MRS than the other archwire groups with no significant difference between group E (193.32 ± 25.89gf), T (244.08 ± 88.83gf), and U (175.82 ± 39.62gf) at 0° bracket angulation (Figure 11: left). At 3° bracket angulation, group P (1459.58 ± 203.38gf) and T (1446.94 ± 220.31gf) showed significantly higher MRS than group E (610.02 ± 53.94gf) and U (700.36 ± 201.89gf) with no significant difference between group P & T and between group E & U at T4 (Figure 11: right).

Table 11. Pairwise comparisons of MRS with a Tukey adjustment based on water immersion time

Water immersion	**T0**					
Archwire group	Bracket angulation	Mean (gf)	SE	Lower 95% CI	Upper 95% CI	Cluster*
T	0°	181.82	56.31	70.05	293.59	a
E	0°	204.24	56.31	92.47	316.01	a
U	0°	302.18	56.31	190.41	413.95	a
E	3°	557.96	56.31	446.19	669.73	b
U	3°	703.02	56.31	591.25	814.79	bc
P	0°	760.22	56.31	648.45	871.99	bc
T	3°	812.96	56.31	701.19	924.73	c
P	3°	1440.78	56.31	1329.01	1552.55	d

- Clusters not connected by the same letter are significantly different

Water immersion	**T2**					
Archwire group	Bracket angulation	Mean	SE	Lower 95% CI	Upper 95% CI	Cluster*
T	3°	210.00	56.31	98.23	321.77	a
E	3°	235.30	56.31	123.53	347.07	a
T	0°	260.24	56.31	148.47	372.01	a
U	0°	261.66	56.31	149.89	373.43	a
E	0°	335.22	56.31	223.45	446.99	ab
P	0°	531.48	56.31	419.71	643.25	bc
U	3°	691.28	56.31	579.51	803.05	c
P	3°	1496.74	56.31	1384.97	1608.51	d

- Clusters not connected by the same letter are significantly different

Water immersion	**T4**					
Archwire group	Bracket angulation	Mean	SE	Lower 95% CI	Upper 95% CI	Cluster*
U	0°	175.82	56.31	64.05	287.59	a
E	0°	193.32	56.31	81.55	305.09	a
T	0°	244.08	56.31	132.31	355.85	a
E	3°	610.02	56.31	498.25	721.79	b
U	3°	700.36	56.31	588.59	812.13	b
P	0°	1105.22	56.31	993.45	1216.99	c
T	3°	1446.94	56.31	1335.17	1558.71	d
P	3°	1459.58	56.31	1347.81	1571.35	d

- Clusters not connected by the same letter are significantly different

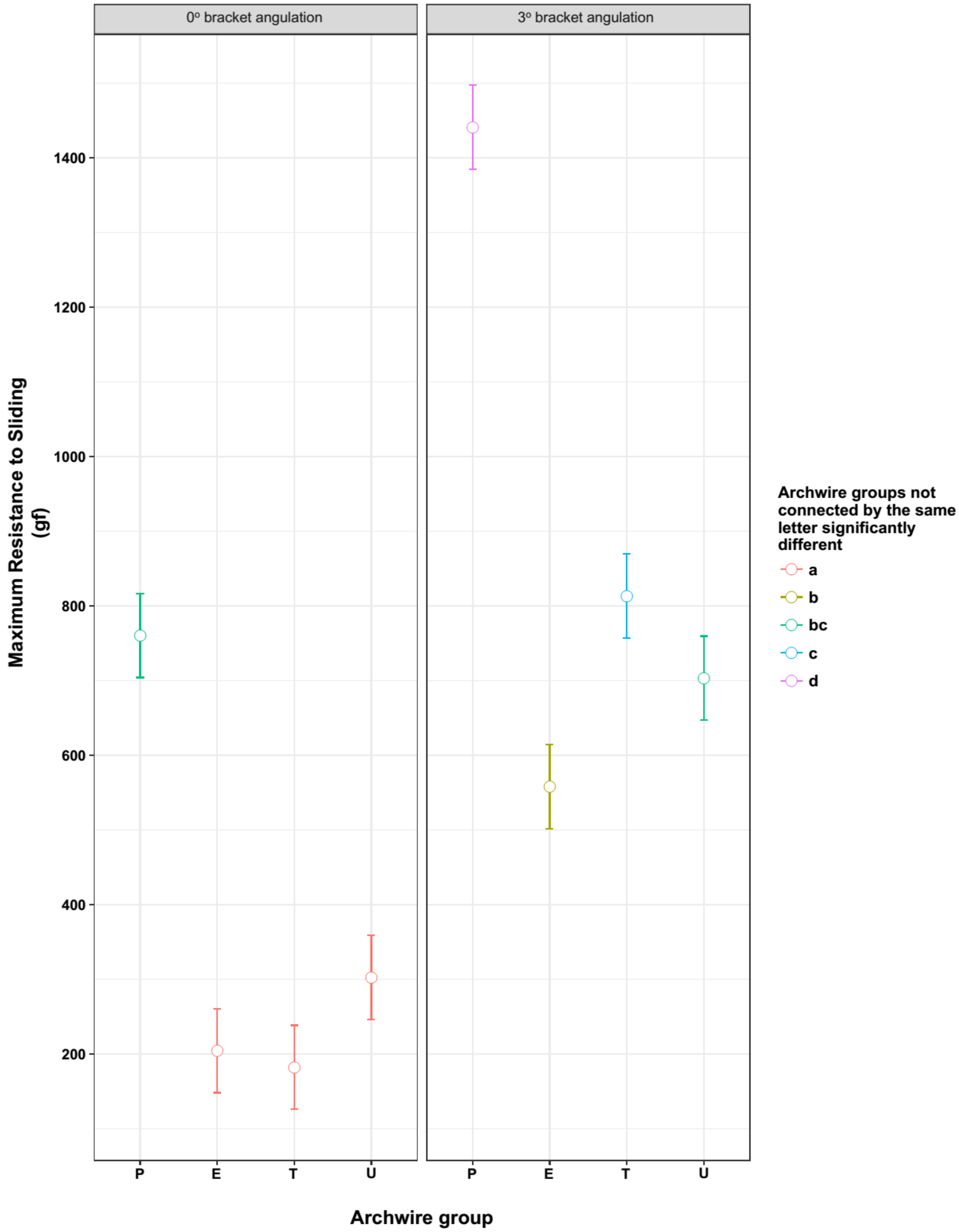

Figure 9. Least squares mean plot of MRS at T0 with standard error

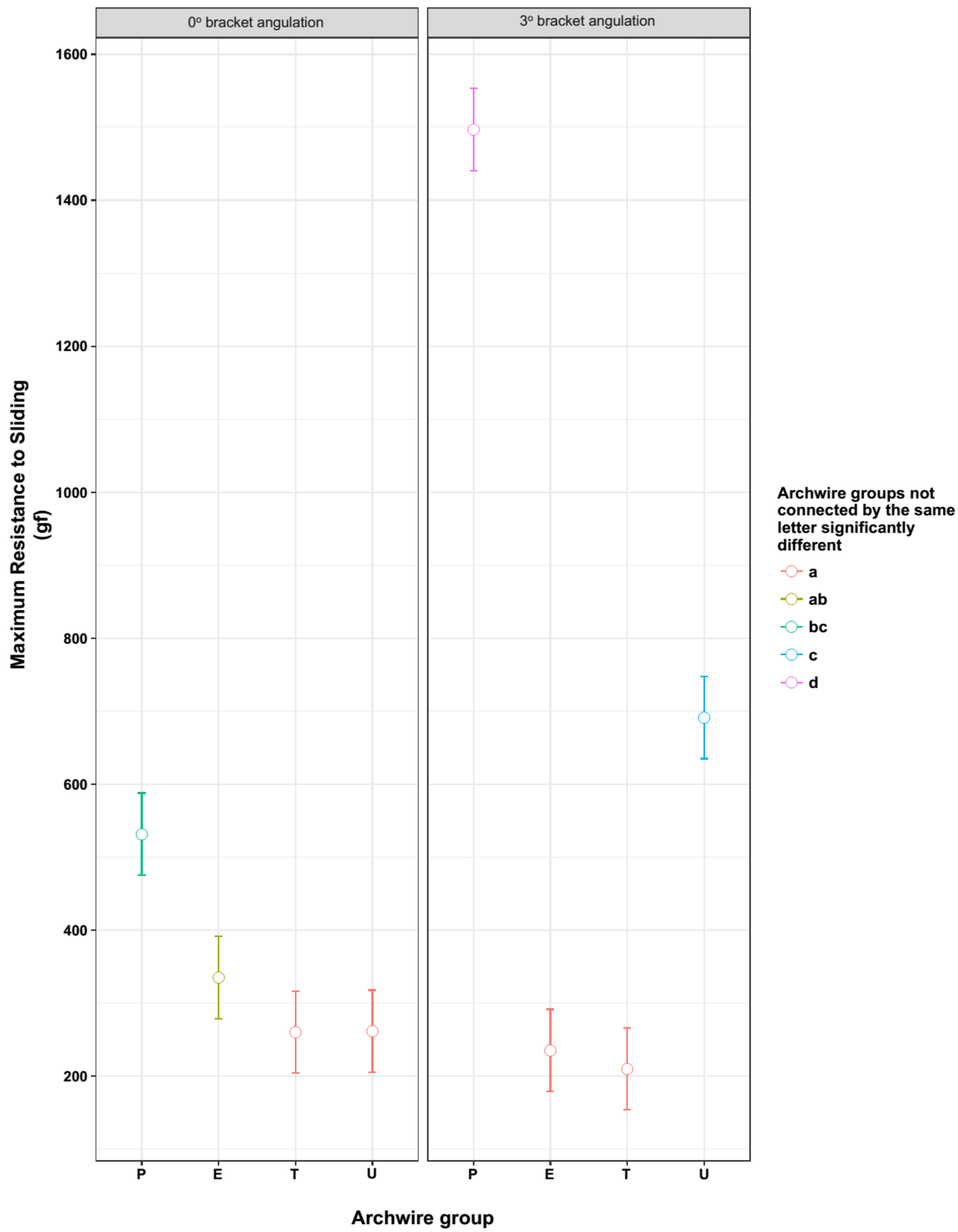

Figure 10. Least squares mean plot of MRS at T2 with standard error

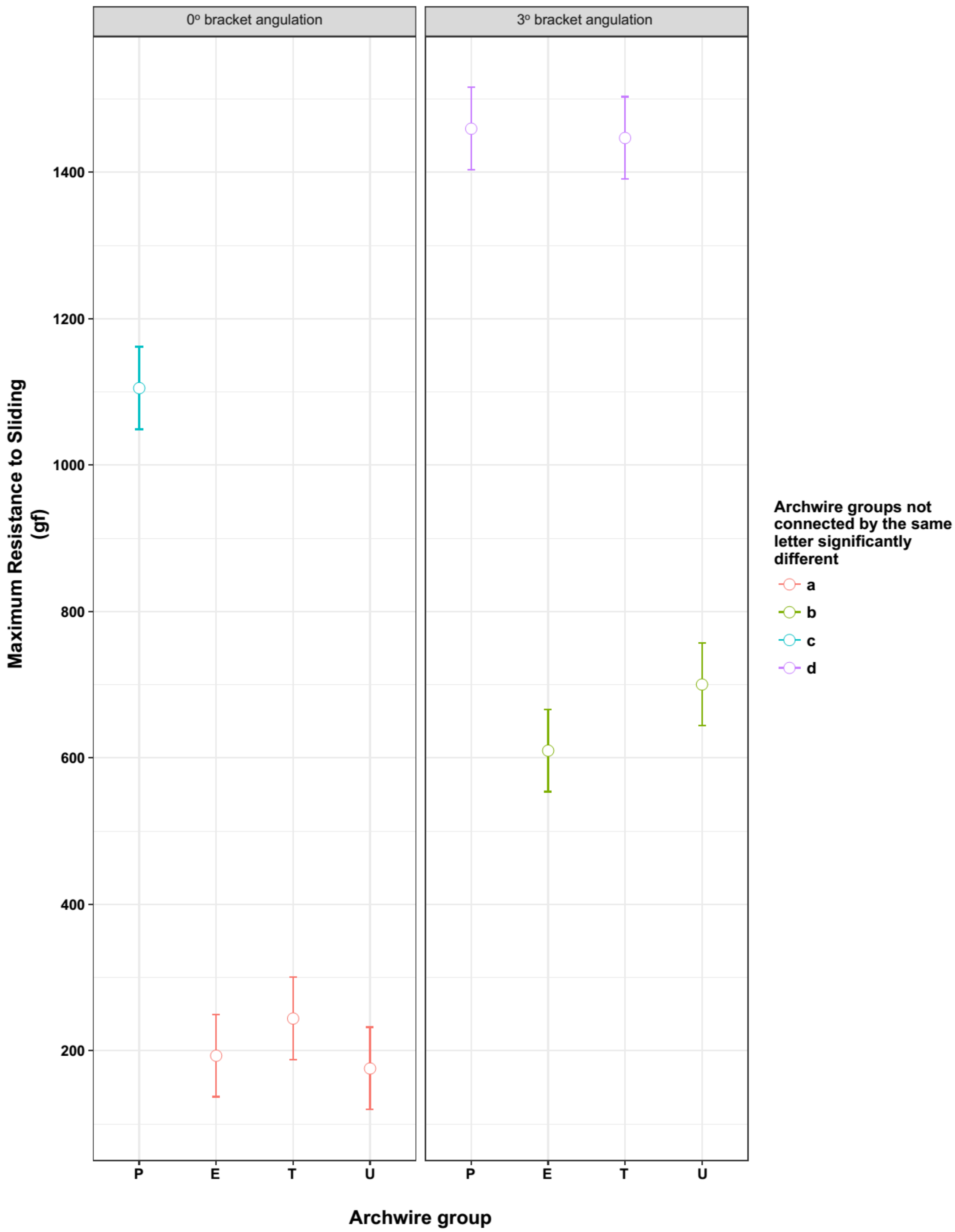

Figure 11. Least squares mean plot of MRS at T4 with standard error

Table 12. Summary of MRS differences between archwire groups at various water immersion times and bracket angulations

Water immersion time	0° bracket angulation	3° bracket angulation
T0	P> E, T, U	P> T> U> E
T2	P> E> U, T	P> U> T, E
T4	P> E, T, U	P, T> E, U

3.3 Examination of surface morphology of archwires after sliding test

The surface morphology of archwires showed changes after water immersion and sliding tests. The counts and percentages of delamination of coated surface of each archwire group after sliding test at each water immersion times at 0° and 3° bracket angulations were listed in table 13. After water immersion before sliding test, only group T showed obvious surface morphological change with swelling spots at T2 & T4 (Figure 14d, g). All the coated archwire groups showed certain amounts of delamination of coating after sliding test at T0, T2, and T4 at 0° and 3° bracket angulation (Table 13, Figure 12, 13, 14). On the surface of uncoated group U, scratching streaks were noted after sliding test at T0, T2, and T4 at 0° and 3° bracket angulation (Figure 15).

Table 13. The counts and percentages of delamination of coated surfaces of archwires after sliding test (n=5 in each test condition)

Water immersion	Bracket angulation	Archwire group		
		P	E	T
T0	0°	5 (33.3%)	4 (26.7%)	2 (13.3%)
	3°	5 (33.3%)	5 (33.3%)	5 (33.3%)
T2	0°	5 (33.3%)	5 (33.3%)	2 (13.3%)
	3°	5 (33.3%)	5 (33.3%)	5 (33.3%)
T4	0°	5 (33.3%)	5 (33.3%)	2 (13.3%)
	3°	5 (33.3%)	5 (33.3%)	5 (33.3%)

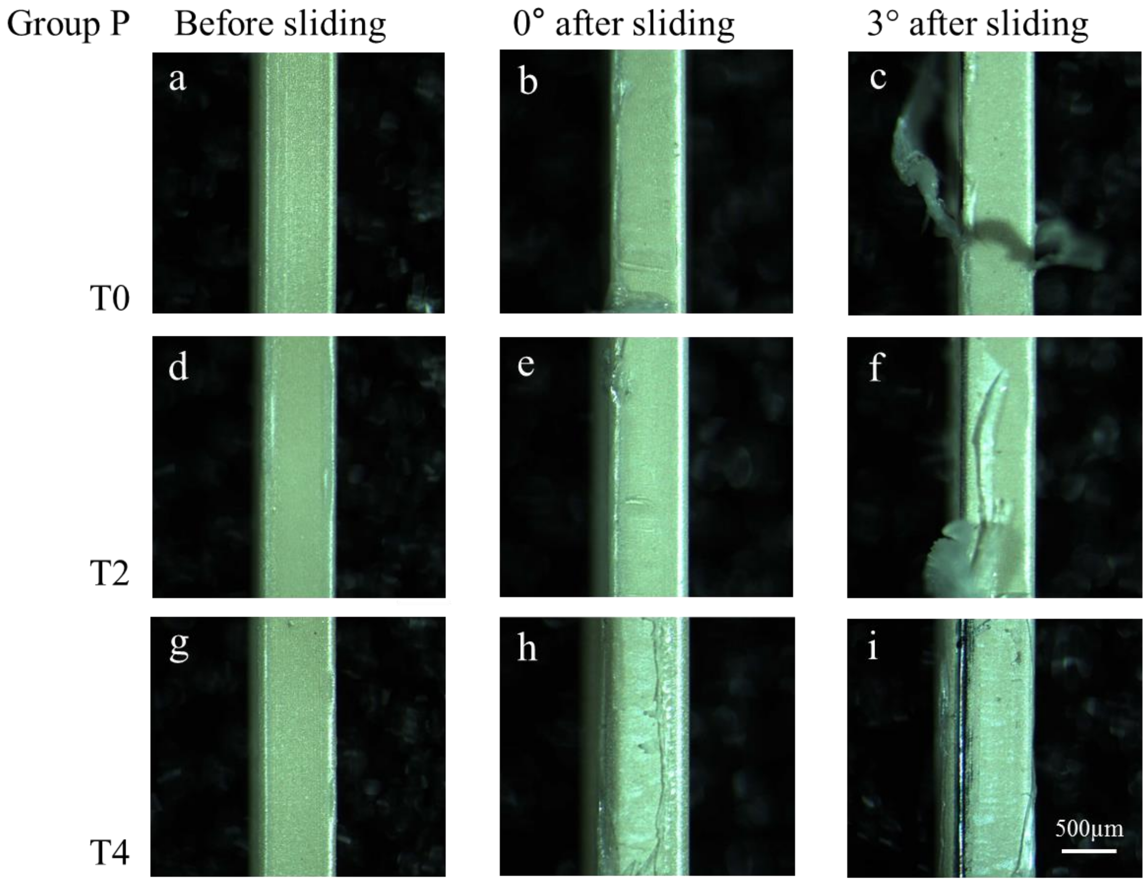

Figure 12. Representative stereo microscope images in group P at T0: (a) before sliding test, (b) 0° bracket angulation after sliding test, (c) 3° bracket angulation after sliding test, at T2: (d) before sliding test, (e) 0° bracket angulation after sliding test, (f) 3° bracket angulation after sliding test, and at T4: (g) before sliding test, (h) 0° bracket angulation after sliding test, (i) 3° bracket angulation after sliding test

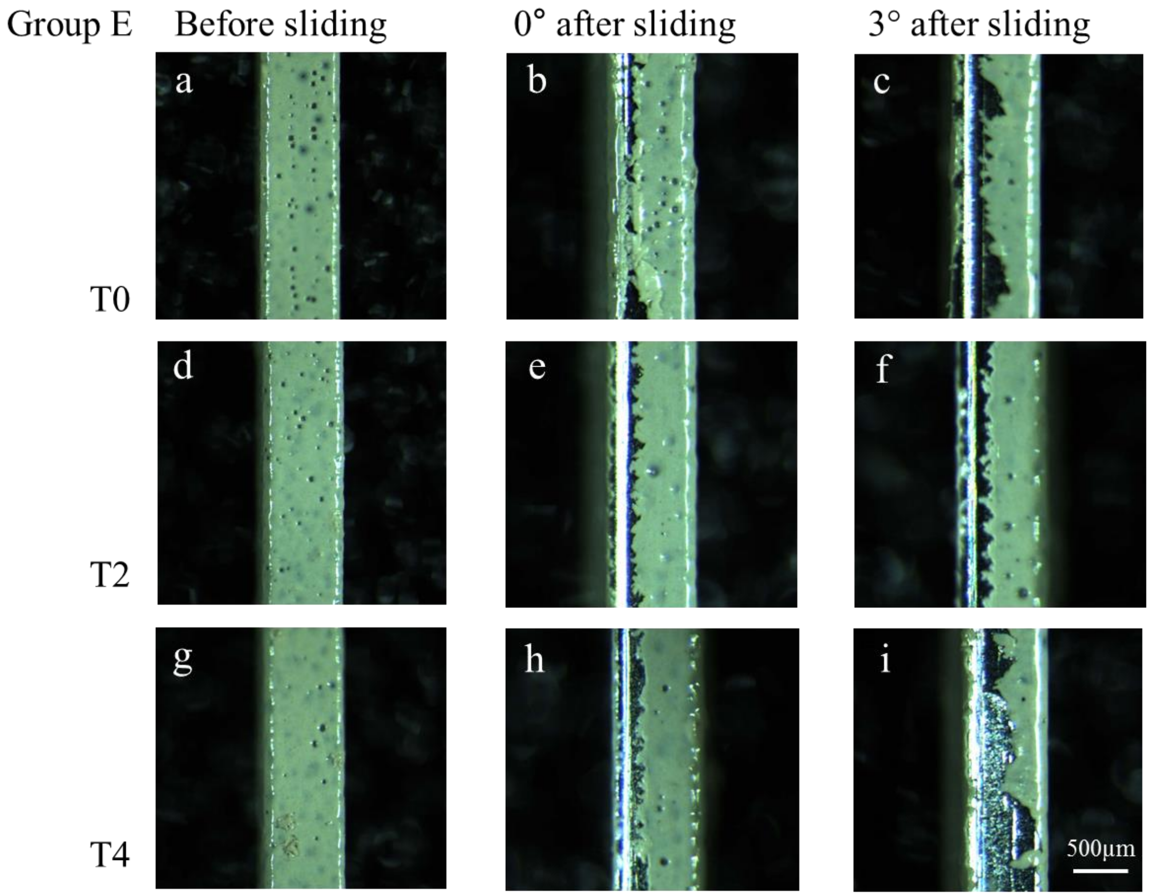

Figure 13. Representative stereo microscope images in group E at T0: (a) before sliding test, (b) 0° bracket angulation after sliding test, (c) 3° bracket angulation after sliding test, at T2: (d) before sliding test, (e) 0° bracket angulation after sliding test, (f) 3° bracket angulation after sliding test, and at T4: (g) before sliding test, (h) 0° bracket angulation after sliding test, (i) 3° bracket angulation after sliding test

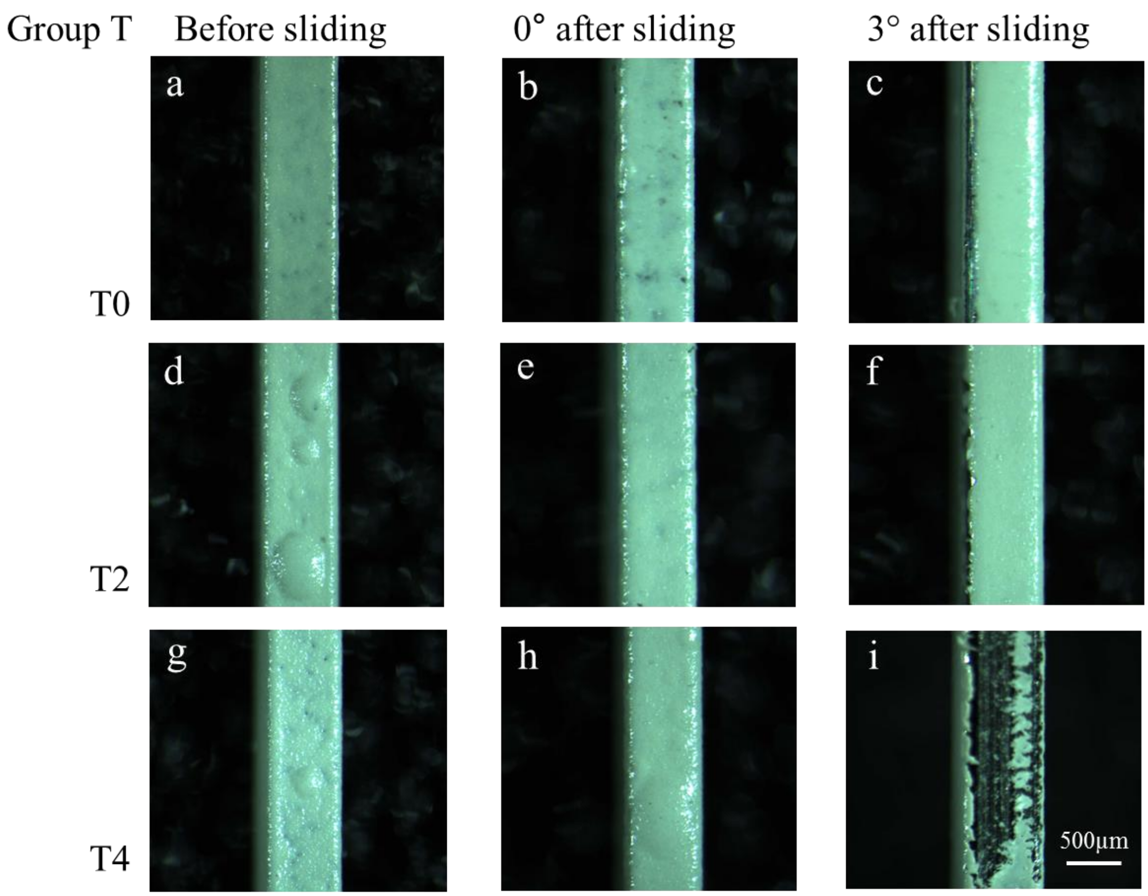

Figure 14. Representative stereo microscope images in group T at T0: (a) before sliding test, (b) 0° bracket angulation after sliding test, (c) 3° bracket angulation after sliding test, at T2: (d) before sliding test, (e) 0° bracket angulation after sliding test, (f) 3° bracket angulation after sliding test, and at T4: (g) before sliding test, (h) 0° bracket angulation after sliding test, (i) 3° bracket angulation after sliding test

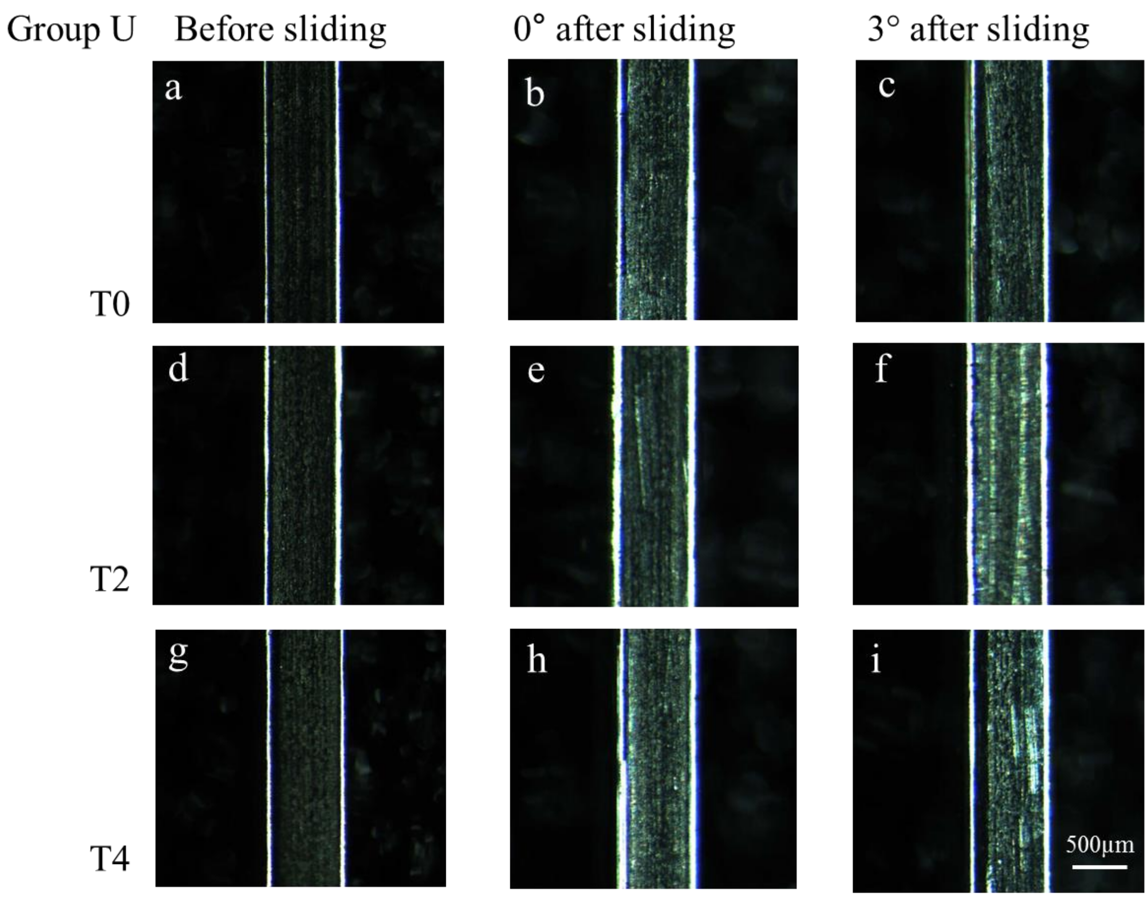

Figure 15. Representative stereo microscope images in group U at T0: (a) before sliding test, (b) 0° bracket angulation after sliding test, (c) 3° bracket angulation after sliding test, at T2: (d) before sliding test, (e) 0° bracket angulation after sliding test, (f) 3° bracket angulation after sliding test, and at T4: (g) before sliding test, (h) 0° bracket angulation after sliding test, (i) 3° bracket angulation after sliding test

Chapter 4: Discussion

In our study, tooth-colored archwires with various coatings showed distinct changes in RS after immersed in D.D. water for a period of time. To understand the changes, we need to examine the nature of RS and the factors affecting it. In general tribology, RS is defined as the motion-resisting force when the two surfaces in contact move to opposite directions.[37] The main parameters affecting the tribological process are material properties, environmental parameters, and geometry of the contact.[30] We immersed various archwires in D.D. water for up to 4 weeks and slid them at 0° & 3° bracket angulations. Therefore, material properties of the archwires, environmental parameters of water immersion, and geometry of the contact at different bracket angulations will be discussed below for the RS changes observed in the present study.

4.1. Effects of material properties of archwires on RS

Tooth-colored archwires were SS archwires coated with various polymers. Coating surfaces of archwires directly contacted brackets during sliding test. After sliding test, some tooth-colored archwires were delaminated and showed the underlying SS archwire. Therefore, it is necessary to examine the effects of material properties of surface coatings and underlying archwire on RS in the present study.

4.1.1 Effects of material properties of surface coating on RS

Currently, there was no published direct evidence between RS and material properties of surface coating on archwires. The possible factors affecting RS in the present study could be explained indirectly from the research about coating materials per se.

Factors affecting RS with thin coating generally are coating hardness, coating thickness, debris in the contact zone, and counter surface roughness.[38] In a descending order, hardness of epoxy resin, Parylene, and Teflon were reported as 35.9GPa,[39] 2.8GPa,[40] and 0.5GPa[41] and coating thickness of epoxy resin, Teflon, and Parylene on tooth-colored archwires were reported as 0.05 mm,[42] 0.025 mm,[43] and 0.01 mm[44]. In the present study, RS of group P was higher than that of group E & T at T0 at 0° bracket angulation in. The discrepancy between the order of these two factors and the order of RS indicated that coating hardness or coating thickness alone could not explain the RS difference between these coated archwires. Since there was no published article about effects of debris from coated archwires on RS, we could not verify the effects of debris on RS as no observation was made about the debris in the present study. As new ceramic brackets of the same brand were used in each experimental group, same counter surfaces of brackets were most likely encountered by archwires as there was no obvious change of bracket surfaces observed under microscope (non-published data). Therefore, the differences in RS between archwire groups unlikely came from the counter surface effect.

4.1.2 Effects of material properties of underlying archwire on RS

To examine the effects of underlying archwire on RS, we need to consider the differences in SS archwires underlying tooth-colored archwires. However, there was no previously published research about differences in material properties of same dimensional SS archwires from different companies. As we did not observe the differences in underlying SS archwires in the present study, we could not evaluate the effects of material properties of underlying SS archwire on RS here.

4.2. Effects of water immersion on RS

Environmental parameters can affect RS.[30] After water immersion, epoxy polymer could be plasticized with reduced hardness and strength. A 20-hour water immersion of 50 um Epoxy resin films decreased their tensile strength by 27.6% and elastic modulus by 33.2% when compared to dry specimens.[22] In the present study, it was very likely that the tensile strength and elastic modulus of epoxy coating decreased after 2- or 4-week water immersion. Since tensile strength and elastic modulus of coating are related to RS,[30] changes of these two properties might lead to changes of RS in group E after water immersion. Very interestingly, RS of group E at 3° bracket angulation showed a decrease from T0 to T2 and an increase from T2 to T4 to the level even above that at T0. The result that RS at T4 was significantly higher than that at T0 agreed with the results of previous article, which showed that epoxy-coated 0.016inch NiTi archwire had significantly higher RS after 30 days immersion in Coca Cola.[45] Currently, there was no published research addressing the changes of physical properties of epoxy-coated archwires related to water immersion. Further research is needed to elucidate the property changes of epoxy-coated archwires after water immersion.

After water immersion, Teflon changed its surface and physical properties.[46,47] Teflon-coated SS archwires showed a significantly increase in numbers of pitting after water immersion for 1 day, 7 days, and 28 days.[46] Teflon and its composites showed a decrease in hardness and tensile strength after 24-hour water immersion.[47] However, there was no difference in RS between at T0, T2, and T4 at 0° bracket angulation in the present study. It is likely that the changes of above-mentioned properties of Teflon coating did not play significant roles in RS or the other changes of physical properties counteracted their impacts on RS in Teflon-coated archwires after water immersion.

Parylene coating has more resistance to water penetration than Teflon and Epoxy coatings.[48] As there was no difference in RS between at T0 and T2 at 0° bracket angulation in group P, it is likely that Parylene coating of group P resisted water penetration up to 2 weeks. The noted increases of RS at T4 at 0° bracket angulation in group P might indicate a dramatic change of RS-affecting parameters between T2 and T4.

In group U, water immersion did not show any effect on RS at 0° or 3° bracket angulations. Since there was no polymer coating on SS archwires in group U, no changes of RS between at T0, T2, and T4 suggested no net change in RS-affecting parameters of SS archwires under up to 4 weeks water immersion.

4.3 Effects of geometry of contact on RS

Geometry of the contacts affects RS.[30] When archwires slide on brackets, three distinct geometries of the contacts present: friction, binding, and notching.[27] The differences in the surfaces changes of coated archwires after sliding at 0° and 3° bracket angulations indicated that various geometry of the contacts happened in the present study.

When archwire-bracket angulation is smaller than the critical angle of binding, such as at 0° bracket angulation in the present study, only classic friction is expected to present. When archwire-bracket angulation becomes bigger than the critical angle of binding, such as at 3° bracket angulation in the present study, binding and notching are expected to present in addition to classic friction. In the present study, RS at 3° bracket angulation was higher than that at 0° bracket angulation in group P & U at T0, T2, and T4 and group E & T at T0 and T4. These results were expected with the involvement of binding and notching in addition to classic friction at 3° bracket angulation. Very interestingly, RS relationship between at 0° and 3° angulations showed distinct patterns in group E & T at T2. In group E, ARS and MRS at 3° bracket angulation were significantly lower than those at 0° bracket angulation. In group T, there was no significant difference in ARS and MRS between at 0° and 3° bracket angulation at T2. As Epoxy and Teflon coatings can reduce the friction coefficient and wear by providing a transfer film on counter surfaces as a solid lubricant[49,50], it is possible that the transfer films of epoxy and Teflon reduced the ARS and MRS in group E and T at T2 at 3° bracket angulation.

4.4 Clinical implication

In orthodontic treatments, there are usually three stages: leveling and alignment, closing spaces/change of intermolar relationship, and finishing. Low RS of archwires is favorable for the orthodontic tooth movements in the leveling & alignment and the space closure by sliding mechanics in which archwires are required to slide on brackets smoothly. In contrast, high RS of archwires is favorable for the orthodontic tooth movements in the space closure by closing loop mechanics and in the finishing as torque & tip control requiring archwires to hold on to the brackets tightly.

In orthodontic tooth movements, archwires usually engage against the corners of bracket slots. This geometry of contacts results in friction, binding, and notching of archwire against the brackets. Therefore, RS at 3° bracket angulation in the present study is more clinically relevant to RS in orthodontic tooth movement. In the present study, group E always showed the lowest RS and group P always showed the highest RS at 3° bracket angulation among coated and uncoated archwire groups. Based on the results, we would recommend the epoxy-coated archwires for the leveling & alignment and the space closure by sliding mechanics and the Parylene-coated archwires for the space closure by closing loop mechanics and the finishing if 0.019x0.025inch SS coated archwires and esthetic sapphire ceramic brackets of 0.022-inch slot are used.

4.5. Limitations, Implications and Future Studies

A wise use of RS is important for an efficient orthodontic tooth movement in the clinic. RS is affected by many factors, such as biological parameters (tissue response, plaque, saliva, etc.), material properties of orthodontic appliances, and geometry of the contacts between archwires and bracekts.[51] Therefore, the more clinically relevant way to evaluate RS is to have an experimental setup with clinical scenarios.[52] Among all possible factors on RS, our study addressed three factors such as coating surfaces, bracket angulations, and water immersion times. With the knowledge gained in this study, we paved a way for a future *in vivo* study for the use of appropriate tooth-colored archwires in different stages of orthodontic treatments on patients.

Chapter 5: Conclusions

The water immersion time, bracket angulation, and surface coating of archwires affected RS distinctly between tooth-colored archwires. Among these three factors, the bracket angulation and the surface coating played major roles in the resistance to sliding. The conclusions of this study are:

1. Water immersion did not affect RS of Parylene-coated and uncoated archwires at 3° bracket angulation up to 4 weeks. At 3° bracket angulation, water immersion decreased the RS of epoxy-coated and Teflon-coated archwires after 2 weeks and increased it after 4 weeks.
2. For all archwires used in the present study, RS at 3° bracket angulation was higher than that at 0° bracket angulation with the exceptions of epoxy-coated and Teflon-coated archwires after water immersion for 2 weeks.
3. RS of Parylene-coated archwires was the highest among coated and uncoated archwires in all experimental conditions.
4. RS of epoxy-coated archwires was the lowest among coated and uncoated archwires in all experimental conditions, except at 0° bracket angulation after water immersion for 2 weeks.

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Appendix- Raw Data

Archwire group	water immersion time	bracket angulation	average load (gf)	maximum load (gf)	ISA (0=no, 1=yes)
P	0	0	516	653	1
P	0	0	507	634	1
P	0	0	479	667	1
P	0	0	630	953	1
P	0	0	617	894	1
P	0	3	1153	1445	1
P	0	3	1113	1401	1
P	0	3	1133	1398	1
P	0	3	1045	1341	1
P	0	3	1356	1619	1
P	2	0	412	571	1
P	2	0	385	610	1
P	2	0	169	262	1
P	2	0	248	529	1
P	2	0	466	686	1
P	2	3	1361	1611	1
P	2	3	1048	1403	1
P	2	3	1124	1468	1
P	2	3	1158	1332	1
P	2	3	1350	1669	1
P	4	0	753	907	1
P	4	0	714	873	1
P	4	0	906	1376	1
P	4	0	998	1455	1
P	4	0	773	916	1
P	4	3	1071	1280	1
P	4	3	1156	1459	1
P	4	3	1152	1409	1
P	4	3	1377	1803	1
P	4	3	1081	1347	1
E	0	0	98	181	1
E	0	0	147	219	1
E	0	0	150	256	1

E	0	0	81	168	0
E	0	0	100	197	1
E	0	3	399	502	1
E	0	3	469	611	1
E	0	3	408	573	1
E	0	3	337	430	1
E	0	3	563	674	1
E	2	0	250	396	1
E	2	0	229	318	1
E	2	0	200	276	1
E	2	0	184	291	1
E	2	0	258	394	1
E	2	3	155	250	1
E	2	3	133	231	1
E	2	3	80	183	1
E	2	3	155	214	1
E	2	3	203	298	1
E	4	0	171	219	1
E	4	0	91	164	1
E	4	0	138	197	1
E	4	0	66	170	1
E	4	0	128	218	1
E	4	3	417	548	1
E	4	3	524	656	1
E	4	3	387	557	1
E	4	3	401	633	1
E	4	3	499	658	1
T	0	0	70	172	0
T	0	0	127	185	1
T	0	0	195	248	1
T	0	0	99	161	0
T	0	0	94	144	0
T	0	3	639	775	1
T	0	3	468	862	1
T	0	3	384	694	1
T	0	3	743	933	1
T	0	3	595	800	1
T	2	0	154	208	0

T	2	0	382	450	1
T	2	0	188	241	1
T	2	0	136	195	0
T	2	0	159	207	0
T	2	3	191	234	1
T	2	3	134	241	1
T	2	3	11	185	1
T	2	3	58	192	1
T	2	3	152	198	1
T	4	0	105	170	0
T	4	0	170	214	0
T	4	0	140	215	0
T	4	0	116	223	1
T	4	0	265	399	1
T	4	3	1567	1764	1
T	4	3	1116	1355	1
T	4	3	1329	1541	1
T	4	3	1120	1401	1
T	4	3	973	1175	1
U	0	0	46	181	0
U	0	0	173	298	0
U	0	0	180	395	0
U	0	0	162	321	0
U	0	0	269	316	0
U	0	3	700	781	0
U	0	3	411	652	0
U	0	3	353	667	0
U	0	3	617	756	0
U	0	3	527	660	0
U	2	0	299	388	0
U	2	0	187	240	0
U	2	0	198	270	0
U	2	0	216	256	0
U	2	0	84	155	0
U	2	3	587	679	0
U	2	3	777	901	0
U	2	3	644	767	0
U	2	3	469	554	0

U	2	3	395	555	0
U	4	0	178	245	0
U	4	0	103	159	0
U	4	0	92	165	0
U	4	0	73	146	0
U	4	0	112	164	0
U	4	3	116	391	0
U	4	3	490	679	0
U	4	3	683	779	0
U	4	3	855	947	0
U	4	3	544	706	0