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FRICTIONAL PROPERTIES OF NOVEL BRACKET SYSTEMS: AN IN-VITRO STUDY

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FRICTIONAL PROPERTIES OF NOVEL BRACKET SYSTEMS: AN IN-VITRO STUDY

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Dentistry at Virginia Commonwealth University.

by

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Abstract

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Orthodontic brackets undergo resistance during sliding that includes classical friction, binding, and notching. Current bracket systems are hampered by these challenging forces. As a result, the clinician usually needs to apply additional forces to overcome the resistance which increases the risk of root resorption and discomfort for the patient. This study evaluated frictional properties of a novel bracket that had polytetrafluoroethylene (Teflon™) coated rollers in its design. Five types of brackets (n = 10, each), including a passive self-ligating bracket, a traditional ligated bracket, a three-dimensionally printed direct metal laser sintering (DMLS) bracket with and without Teflon™ rollers, and computer numeric controlled (CNC) machine milled bracket with Teflon™ rollers were tested. The peak resistance values were assessed at 0°, 4°, and 8° of tip on a 0.019 x 0.025” arch wire. At 8° of tip, the DMLS and the CNC milled bracket systems, both with Teflon™ rollers, exhibited less friction as compared to the other brackets tested ($p<0.05$). The data suggest that Teflon™ rollers could potentially decrease resistance to sliding during orthodontic movement.

Introduction

The foundational mechanics of conventional orthodontic therapy utilizes an arch wire sliding through a metal bracket. The biologic process of bone remodeling takes place when a force is applied to the bracket directly with elastics, springs, or arch wires. Furthermore, as the force is applied, a series of tipping and uprighting movements occur, a phenomenon of binding and letting go where the bracket seemingly “jigs” and “jogs” along the wire.[1,2]

During sliding mechanics, the bracket is subjected to various forms of resistance. The bracket and the arch wire encounter classical friction that is dependent on a coefficient of friction and a normal force ($F = \mu N$). Classical friction occurs when the bracket can freely slide on the wire. Once the wire contacts the bracket, binding occurs and the harder material creates a localized stress that exceeds the yield strength of the softer material. The materials begin to interlock that increases overall resistance. [2] Notching occurs as grooves are formed by a combination of gouging and cutting in the wire surface when the motion ceases. These conditions contribute to an increased resistance to sliding mechanics.[1] In addition to classical friction between the bracket and the arch wire at nonbinding angulations, binding and notching phenomena at critical angulations also impede sliding mechanics.[1] The effect of binding and notching has a greater impact on overall resistance as the contact angle between the bracket and the arch wire increases during tipping. Around 7° of tip, binding is estimated to be 80% of the resistance and classic friction makes up the rest. At 13°, almost all of the resistance (99%) is contributed to the binding effect.[3]

In the literature, there is a plethora of research on the amount of resistance during sliding mechanics that report a force loss as great as 74% due to friction. [1,4,5] To compensate for the force loss, the practitioners are obliged to use higher orthodontic force levels which may increase the risk for root resorption.[6] If a more efficient bracket with less friction were available, the orthodontist would be able to carry out the treatment while applying ideal force levels to the patient's teeth. Furthermore, lower force application with less pressure and patient discomfort may decrease the incidence of root resorption, a commonly anticipated sequelae of orthodontic therapy.[6,7]

In the literature, there are many studies that investigated the material properties of brackets and wires and their effect on friction.[8–16] Akaike et al[8] reported a significant reduction in static friction when diamond-like carbon coated archwires were used.[8–10] Cha et al found[11] silica coating on archwires was effective in reducing friction resistance considerably as compared to other ceramic and conventional stainless steel brackets. Wei et al[15] discovered that carbon nitride film coating of an orthodontic archwire reduces friction in dry and artificial saliva conditions. Teflon™ coating has also been shown to reduce friction when applied to an archwire.[12] Furthermore, hard chrome carbide coatings designed to make the archwire more esthetic exhibited significantly less friction as compared to uncoated stainless steel controls.[16] On the other hand, brackets designed to "reduce friction" have not been as beneficial as they were marketed.[13] For example, only passive self-ligating bracket designs are shown to have lower friction and resistance compared to active self-ligating brackets and conventional twin brackets.[14]

A possible solution to the friction problem is to incorporate a roller mechanism into the bracket design to allow the wire to overcome binding and notching. Coating the rollers with Teflon™ would also result in decreased friction. To mass produce a complicated roller bracket system with multiple parts is generally challenging with traditional manufacturing methods. However, three-dimensional printing is a recent technology capable of fabricating complex structures with accuracy, precision, and cost-effectiveness.[17] James et al[18] noted three-dimensionally printed copings for crown margins to be clinically acceptable within 120 µm of a gap as compared to those fabricated with the casting and milling methods. Furthermore, Jackson et al[17] reported that three-dimensionally printed brackets manufactured with direct metal laser sintering (DMLS) were more accurate and precise than the control brackets such as Damon Q brackets.

In the previous research by Blackburn et al[19], a novel bracket system with Teflon™ coated rollers was evaluated to determine whether the novel bracket design could decrease the friction. The study simulated sliding mechanics for canine retraction after a first premolar extraction to assess resistance to orthodontic movement due to friction. Since during space closure brackets experience the highest amount of tipping of around 7 degrees, the novel bracket system was tested at 0, 2, 4, 6, and 8 degrees of tip angulation.[20] The frictional force of the experimental group was compared to those of conventional brackets (control). The authors reported that the novel bracket system with Teflon™ rollers exhibited the lowest friction at 0 degrees of tip compared to the other bracket groups tested. However, there were no significant differences in friction at 2°, 4°, 6°, and 8° of angulations among the groups.[19] Limitations of the previous study included small roller slot size and the rough surface finish of the rollers due to the fabrication process. Nevertheless, the previous investigation yielded favorable results indicating a potential benefit of using Teflon™ rollers to decrease friction during sliding mechanics in orthodontics. Furthermore, the study provided useful information on how to further improve the bracket design. The recommendations included increasing the roller slot size diameter to allow for proper clearance for the part freely move and improving the surface finish of the roller indicating a more precise cutting process.[19]

The purpose of the current study is to evaluate the frictional characteristics of a novel bracket design. Specifically, three-dimensionally printed direct metal laser sintering (DMLS) and computer numeric controlled (CNC) machine milled bracket systems, both with Teflon™ rollers, were tested for resistance to sliding mechanics.

Materials and Methods

In this study five types of brackets (n=10, each) were used: a passive self-ligating bracket, (Damon Q bracket, Ormco Corp, Orange, CA), a conventional twin bracket, (Victory Series™, 3M Unitek, Monrovia, CA), a direct metal laser sintering (DMLS) roller bracket with Teflon™ rollers(DuPont, Wilmington, DE), a DMLS roller bracket with non-Teflon™ rollers, and a computer numerically controlled (CNC) milled bracket with Teflon™ rollers (Figure 1 and Figure 2). The DMLS brackets were manufactured at Protolabs (Maple Plain, MN), and the CNC milled brackets were fabricated by Micro Precision Parts Manufacturing Ltd. (Qualicum Beach, BC). All bracket types had 0.022" slot height and were made of stainless steel. The Teflon™ coated rollers were fabricated with 0.020" diameter so that they would be accommodated in the 0.023" size roller slots in the novel bracket design (Component Supply Company, Sparta, TN). The brackets were tested at 0°, 4°, and 8° of tip. The peak frictional force was recorded in Newtons.

The study protocol was similar to that used by Blackburn et al.[19] The testing jig was comprised of two parts. One part was the baseplate designed to hold a straight wire with 300 g of tension. The other part of the jig was intended to hold the bracket at varying degrees of tip (Figure 3). The length of the test wire was set at 18.4 mm to represent the clinical conditions present during a premolar extraction case.[21] Tensioning was completed by compressing the adjustment spring until the force level of 300 g was visible on the MTS Insight 30 load cell testing machine (MTS Insight 30 MTS, Eden Prairie, MN) (Figure 3).[19] A line was marked on the test stand jig to denote the travel distance of the wire tensioner and to ensure tension on the wire was the same amount at each testing.

Each bracket was mounted on a 0.021” x 0.025” stainless steel wire (Figure 4). The wire was slotted in the bracket with composite resin (Transbond XT, 3M Unitek, Monrovia, CA) on the base of the bracket and on the metal mounting rod. The hinge portion of the test stand was rotated up to be parallel and in contact with the bracket. The vertical axis adjustment screw was loosened so that the vertical hinge component could freely rotate (Figure 3). A torpedo level was utilized to ensure the vertical hinge axis was truly vertical and parallel with the wire. The set screw for the mounting rod was tightened to the vertical hinge axis (Figure 5). The jig hinge that could be rotated by 1° increments was initially set at 0° and a wire was placed to hold the jig tip adjustment (Figure 6). At this time, the composite resin was polymerized with a curing light for 10 seconds on both sides of the bracket (Figure 4). Each sample was mounted in a way that brackets were attached passively with no torque.[19]

To evaluate friction, brackets in each group were tested at 0°, 4°, and 8° of tip on a new 0.019” x 0.025” archwire. The brackets were randomized; however, once a bracket within a group was chosen, it was tested at all three degrees (0°, 4°, and 8°) consecutively. An elastomeric ring was replaced following each bracket to account for any wire bending or fatigue during the testing.

When testing began, a bracket with associated metal mounting rod was mounted in the hinged portion of the testing jig. The test wire of 0.019” x 0.025” size was mounted and the bracket was rotated into position. The hinge portion was confirmed to be vertical with the wire by use of the torpedo level. The mounting rod set screw was then tightened (Figure 5). The bracket was ligated to the wire with an elastomeric ring (American Orthodontics, Sheboygan, WI). Each bracket was moved up by 3.7 mm to represent the distance between the distal edge of an upper second premolar bracket and the mesial edge of a first molar tube. The MTS Insight 30 load cell testing machine was used to measure the frictional force in Newtons. A 0.032” round stainless steel wire was used to pull the bracket under the tie wing (Figure 3). The torque was set at zero with the white torque set (Figure 7). The 0.032” stainless steel wire was brought up under the tie wing but was not touching the bracket. The MTS Insight 30 was calibrated to zero. The 0.032” round wire was then brought up until just under the tie wings and a load was read on the machine and then it was slightly backed off. Using the TestWorks Elite software (TestWorks, Eden Prairie, MN), the maximum force peak was recorded over a wire span of 3 mm at a speed of 5 mm/min. After every 12 runs, a friction test was conducted where a bracket was pulled by a 0.032” round stainless steel without being attached to the 0.019”x 0.025” arch wire to measure the inherent friction forces in the system.

Peak frictional force was compared between the 5 types of brackets at each of the 3 angulations using one-way analysis of variance (ANOVA). Post hoc pairwise comparisons between each bracket type were adjusted using Tukey’s adjustment for the p-value calculations. The significance level was set at 0.05. SAS EG v.6.1 (SAS Institute, Cary, NC) was used for all analyses.

Results

A total of 45 brackets for each of the five bracket types (n = 10) except for the CNC milled with Teflon™ rollers (n = 5) were tested at 0, 4, and 8 degrees of tip. In addition, the overall static friction of the system was tested 14 times. The results showed that the friction was relatively constant with an average of 0.18 N, ranging from 0.11 - 0.25 N (±0.04). The means and standard deviations for the peak sliding force based on the bracket type and angulation are given in Table 1 and Figure 8. At each of the 3 angulations, there were significant differences in the peak sliding resistance between the bracket and the archwire among the 5 brackets ($p < 0.001$, Table 2).

At 0°, the Damon Q brackets exhibited significantly higher sliding resistance to the archwire than CNC Milled Teflon™ (1.9 N vs 1.4 N, $p < 0.0001$) and DMLS Teflon™ brackets (1.9 N vs 1.5 N, $p < 0.05$). None of the other comparisons were statistically significant.

At 4°, the Damon Q and DMLS non-Teflon™ brackets were not statistically significantly different from each other ($p = 0.9998$) and had higher sliding resistance than the remaining three bracket groups (CNC Milled Teflon™, DMLS Teflon™, Victory Series™; $p < 0.03$). The differences among CNC Milled Teflon™, DMLS Teflon™, and Victory Series™ were not statistically significant ($p > 0.50$).

At 8°, CNC Milled Teflon™ and DMLS Teflon™ brackets had significantly lower sliding resistance ($p < 0.05$) than all other bracket systems, but they were not statistically significant between to each other ($p = 0.9690$). When comparing DMLS Teflon™ group with the Victory Series™ group, the observed difference was 1.96 N with a p-value that was nearly statistically significant ($p = 0.0517$). This difference was deemed clinically significant and labeled as significantly different in Table 2. Victory Series™ brackets and DMLS without Teflon™ brackets were not significantly different (p = 0.6377). Also, DMLS without Teflon™ and Damon Q brackets were not significantly different (p = 0.1564).

Discussion

In orthodontics, archwire frictional resistance is a complex phenomenon. During sliding mechanics, a bracket undergoes classical friction at 0° of tip when it can freely slide along an archwire. In classical friction, the bracket initially holds still until the static friction is overcome which results in a peak in force (Figure 9). After the peak force, a decrease and leveling out occurs. As the bracket travels along the archwire in a continuous motion, the force curve levels off while the bracket is experiencing kinetic friction. However, as the angulation of tip increases, the bracket begins to experience binding and notching. The binding and notching can cause the bracket to “jig” and “jog” along the archwire.[1–3] The force to extension curve reflects this “jig” and “jog” movement with a series of dips and buildup of resistance as the bracket is pulled along the archwire (Figure 10). In this study, the force to extension curves showed an increase of resistance force with an increase of angulation. This reflects similar findings reported in previous studies. [19,22,23] In several investigations, bracket to archwire resistance was evaluated by pulling the bracket along the archwire.[3,19,22–24] However, in some studies the bracket was held by a fixture and the archwire was pulled through the bracket slot.[13,25] These investigations found that resistance forces increase as the angulation increases. Therefore, given the nature of these setups, it is possible that the bracket does not “jig” and “jog” along the wire as it does in vivo. Pulling the bracket, which was the method for this study, may have simulated the force application and the resistance forces during sliding mechanics in vivo.

In this study, a total of 152 samples were tested to evaluate the frictional properties of 5 different types of brackets. One of the CNC Milled brackets failed at the resin composite and the test stand interface while being set at the angulation of 8° after it had been run successfully at 0°

and 4°. That bracket was retested later at 0°, 4°, and 8° of tip. The two runs at 0° and 4° were removed from the sample set since that bracket mounting failed.

The test stand used in this study pulled the bracket along the archwire which more closely simulates in vivo sliding mechanics. The static friction of the test stand was evaluated periodically throughout the testing to determine the inherent friction in the system (0.18 N ± 0.04 N). In the previous study, Blackburn et al,[19] the hinge axis screw was not adjusted and that may have potentially added to the inherent test stand friction (0.733 N ± 0.029 N). Contrarily, in this study, the hinge axis screw was fully loosened to remove any possible friction resulting from the rotation of the vertical portion of the fixture as the bracket is pulled along the wire.

Blackburn et al[19] introduced the concept of rollers with Teflon™ coating in the bracket design as a potential way for reducing resistance between a bracket and an archwire. In that study, an initial bracket design with commercially available Teflon™ coated rollers was tested. Due to time constraints and manufacturing flaws at the time, that study had limitations. Therefore, recommendations for future studies included the use of larger Teflon™ coated rollers and a more precise cutting process resulting in smoother edges on the rollers. It is possible that the rollers in the previous study were too small to be loaded and to freely rotate. Therefore, the previous novel bracket design may not have fully realized the benefit of a roller. Also, the use of distal end pliers in the cutting process could have left burs at the end of the rollers that could have impacted resistance to freely rotating. Therefore, in the current study, the size of the rollers was increased from 0.010” to 0.020” in diameter and the size of the roller slot was increased to 0.023”. Also, the roller was supported on the bracket base; however, it was open to the wire side of the bracket so that the rollers were visible to the exterior side of the bracket. The design modifications were developed for improvement and better understanding of the roller's impact on sliding resistance.

Pilot tests were performed to evaluate the effect of Teflon™ versus non- Teflon™ rollers, machine cut versus manually cut roller ends, and the use of elastic ring on the friction. For the initial tests, the DMLS brackets (n = 4) were tested at 0° and 7°. The results indicated that machine cut rollers showed no statistical significance at 0° and 7° as compared to manually cut rollers. However, there was a statistical difference between the Teflon™ coated and non-Teflon™ coated rollers at 0° (p = .001). Therefore, it was decided not to further evaluate machine cut rollers given the pilot test results, but that it was pertinent to test Teflon™ coated rollers as compared to non-Teflon™ coated rollers. Another finding of the pilot studies was that the resistance increased after initial static friction, especially at higher angulations of tip.

In the previous study, Blackburn et al[19] evaluated resistance during first 0.5 mm, on the contrary, Hamdan et al[22] measured the peak resistance force during the entire test run of 11 mm and found peak resistance values past 0.5 mm. Therefore, in the current study, it was chosen to maintain the test protocol of 3 mm by Blackburn et al[19], but evaluate the peak resistance over the entire test distance.

The results of the current study suggest that the rollers and Teflon™ coating has a potential to reduce resistance between the bracket and archwire. The decrease in resistance for the Protolabs Teflon™ coated rollers group and CNC Milled Teflon™ coated roller group could be due to the Teflon coating as compared to the rest of the brackets (Table 2). Therefore, it is possible that Teflon™ coating may reduce resistance between bracket and archwire. Teflon™ is characterized by a completely fluoridated chain molecule that has anti-adherent properties that enables a low coefficient of friction (μ = 0.04).[12] Samples in the non-Teflon™ coated roller, Victory Series™, and Damon Q groups were significantly higher in resistance at 8°. The rollers seemed to provide some benefit at 0°, but this was not evident at 4° or 8° except when the rollers are Teflon™ coated. However, the rollers may still offer an advantage when it comes binding. It is believed that chewing may aid in binding reduction due to the mandibular bone flexing and the angle between the bracket and archwire changes.[26] In a similar way, rollers may allow for the bracket to archwire angle to change due to flexing and turning within their slot as the bracket slides along the archwire.

This study is in agreement with previous work implicating that coating can reduce resistance force.[12,27] Farronato et al,[12] discovered that the average friction value for Teflon™ coated archwires was 48% (2.75 N) less than uncoated archwires. Stannard et al,[27] found the coefficient of friction to be less than 0.02 under dry conditions against stainless steel.

The clinical implications of this study are that a practitioner could treat a patient with Teflon™ coated roller brackets and the tooth movement may require less force. At 0°, the peak force for the brackets in the DMLS Teflon™ coated rollers group and CNC Milled with Teflon™ coated rollers group were 0.16 N and 0.25 N less, respectively as compared to Victory Series™. At 4°, the force for the CNC Milled with Teflon™ coated rollers group was 0.6 N less as compared to Victory Series™. At 8°, the DMLS Teflon™ coated rollers group and CNC Milled with Teflon™ coated rollers group were 1.96 N and 2.42 N less, respectively as compared to Victory Series™. When stretching an elastomeric chain for premolar space closure retraction, the force level can be as high as 3.52 N based on the in vitro study by Kim et al.[28] Therefore, a clinician would be adding a significant amount of force to the patient's teeth to achieve tooth movement with a Victory Series™ as compared to the novel brackets with

Teflon™ coated rollers. The increased force comes with an increased risk for discomfort or root resorption.[6,7] The elastomeric force in the study by Kim et al[28] is greater than the friction at 4° of tip experienced in this study. Therefore, the Teflon™ coated rollers could provide some benefit to friction reduction. The Teflon™ coated rollers would require less force, therefore a clinician could theoretically plan to use lighter elastomeric chain to achieve the same result of tooth movement for canine retraction.

In this study, the resistance forces were higher for all brackets at 0°, but lower at 4° and 8° of tip when compared to the results of the previous investigation.[19] The differences could be due to test stand setup where the hinge axis screw was not adjusted in the previous work. In the current research, the hinge axis screw was loosened fully to allow the vertical test stand support to rotate freely, like a tooth in the mouth being pulled by an elastic chain. It is possible that the testing condition would decrease the test stand resistance which could explain the lower resistance at 4° and 8° of tip. Also, the test protocol utilized a torpedo level during bracket mounting and experiment setup to ensure the test stand was as vertical as possible when the bracket was pulled vertically up the wire. This additional step would reduce any horizontal forces or vectors that could impact the resistance force measured. Also, the higher resistance values at 0° could be because it was decided not to subtract the test stand friction from the test data in this study.

Blackburn et al[19] found the brackets in Damon Q and experimental groups had the lowest resistance values for 0°. However, the current study found the passive self-ligating Damon Q to be the highest resistance values at 0°, 4°, and 8° of tip. Previous studies demonstrate that self-ligating brackets have significantly lower resistance to sliding at 0° of tip.[14,29,30] However, Redlich et al[13] reported that although self-ligating brackets claim to have a reduced friction, this is not always the case. It was found that reduced friction of self-ligating brackets is controversial when tested in vitro.[13] The Damon Q brackets that were tested in this study had also been previously used in the Blackburn et al[19] study. A risk of repeated use may increase friction resistance; however this was not evident with the Victory Series™ twin brackets.[31] Nevertheless, the results of this study are similar to Hamdan et al[22] for Victory Series™ at 0° and 8° of tip angulations.

One of the limitations of the current study was the in vitro test setup. The friction was tested in a dry environment as compared to a simulated human saliva or wet environment. Sliding in a wet environment does not add friction, and in fact it can potentially reduce friction.[23,27] Also, an elastomeric ring was used to ligate the bracket to the archwire that introduced friction to the testing unit. However, some studies found that ligation method did not impact resistance force.[23,32] In this study, the speed of the test was set at 5 mm/min similar to research protocols in previous investigations by Blackburn et al[19] and Hamdan et al.[22] It is well known that tooth movement varies with an average rate around 1mm per month or 2.3×10^{-5} mm/min.[33] Therefore, the testing condition in our investigation was much faster than average tooth movement rate. According to Yanase et al,[5] resistance forces tend to increase as the bracket slides faster along the archwire. Also, in this study, only a single operator mounted the brackets and performed the tests. An intrarater reliability analysis was not conducted since the results showed small standard deviations indicating a precise test setup and test run execution. Future studies would benefit from having multiple trained and calibrated operators to conduct an interrater reliability analysis of the test method.

Several aspects of the experimental design could be improved in the future to yield more data and results. In the current study, the test trials only pulled the bracket 3 mm up the archwire which was the protocol implemented by Blackburn et al.[19] However, Hamdan et al[22] moved the brackets a distance of 11 mm which had some runs with a peak force beyond 3 mm of distance. It is generally recommended to run the test the full 11 mm to replicate the clinical conditions for first premolar space closure. The type of archwire and bracket slot size may have an impact on the resistance. In this study, stainless steel archwires were utilized. Stainless steel has been shown to have the lowest resistance force when compared to other materials.[21] Therefore, testing the novel bracket with other archwire types would be beneficial to further optimize the space closure.

The novel brackets with rollers were manufactured utilizing DMLS process and CNC milled process. The DMLS and CNC milled processes have a tight tolerance that was clinically acceptable for the margin of a crown of 120 µm.[18] The DMLS process was also evaluated for bracket slot dimension and found to be more accurate than Damon Q.[17] However, it would be beneficial to evaluate the novel brackets to ensure that resistance force reduction is achieved without compromising slot integrity. This could be accomplished by using a high-resolution measurement microscope to evaluate bracket slot of a bracket with rollers. However, the results show that a bracket that implements rollers and Teflon™ coating could prove beneficial for reducing overall bracket to archwire resistance at critical binding angles during space closure mechanics.

Conclusions

1. Brackets in the CNC Milled with Teflon™ rollers and DMLS with Teflon™ rollers groups showed the lowest resistance to archwire sliding at 0°, 4°, and 8° of tip angulation.
2. The DMLS Non-Teflon™ brackets and Damon Q brackets showed the highest resistance to archwire sliding at 0°, 4°, and 8° of tip angulation**.**
3. For all brackets, resistance increased as the tip angulation increased.

Figures

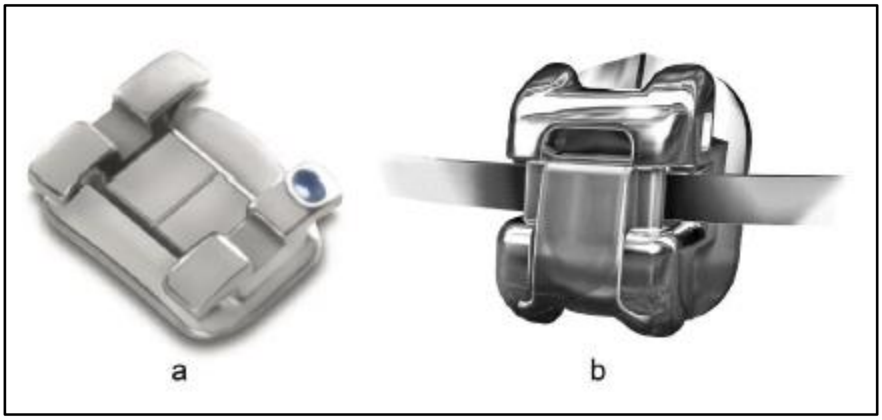

Figure 1: (a) Victory Series bracket, 3M Unitek; (b)Damon Q bracket, Ormco

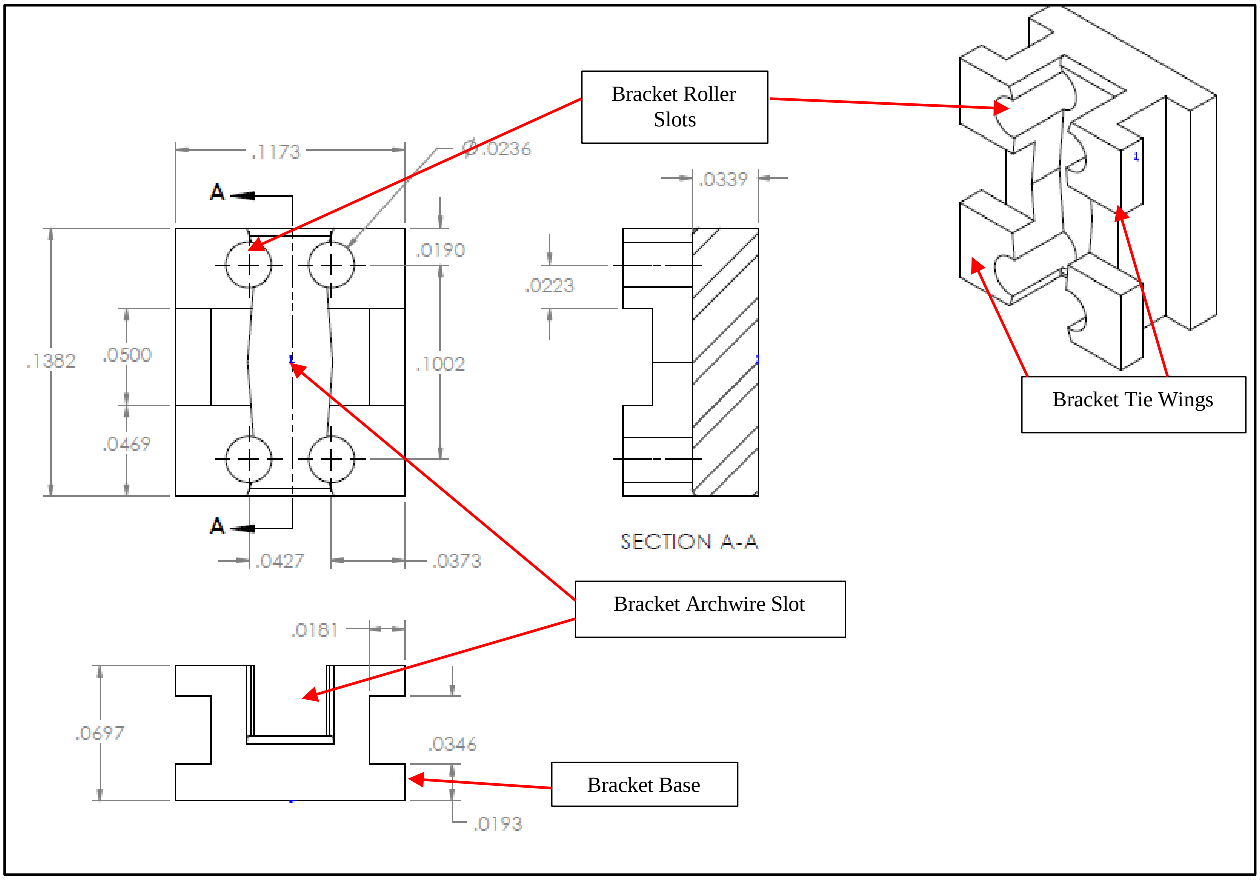

Figure 2: Novel Roller Bracket Design

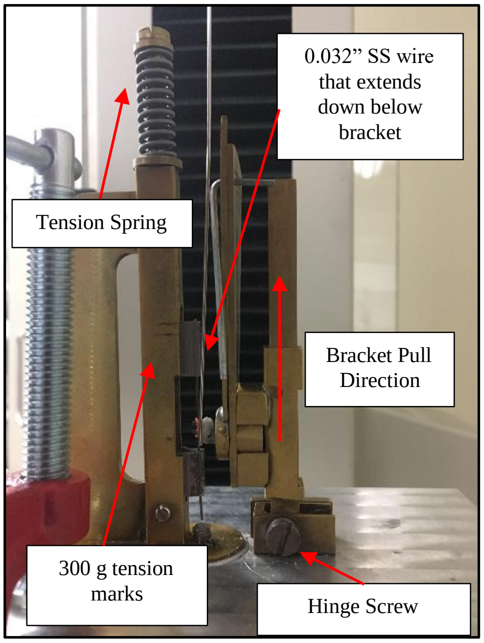

Figure 3: Jig Test Stand Tension Setup
The hinge screw was fully loosened to reduce resistance as the hinge vertical member would rotate. The tension spring is compressed by the MTS 30 Instron until 300 g is measured. A line was marked to mark the length where the wire would need to be cinched to repeatably tension the wire 300 g.

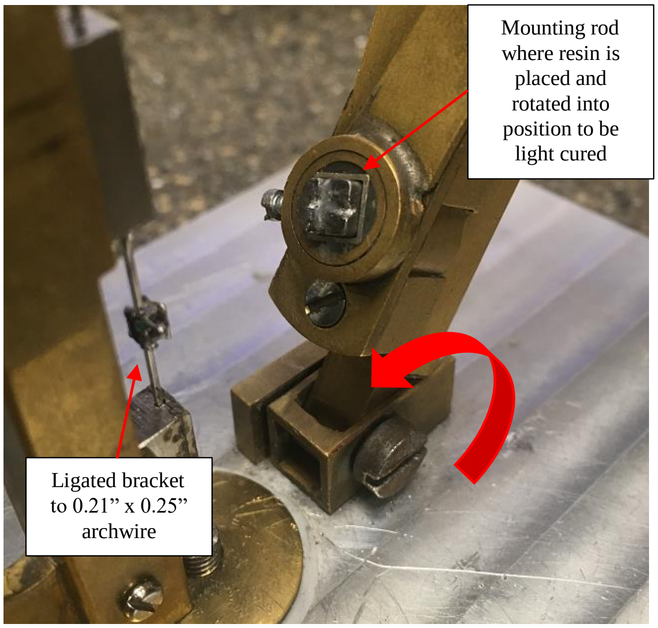

Figure 4: Bracket Setup
During bracket setup, a bracket is mounted on 0.21"x 0.25" wire and a mounting rod is placed in the vertical hinge axis member. Resin is placed on the mounting rod and rotated into place so that the resin can coalesce with the bracket base and light cured.

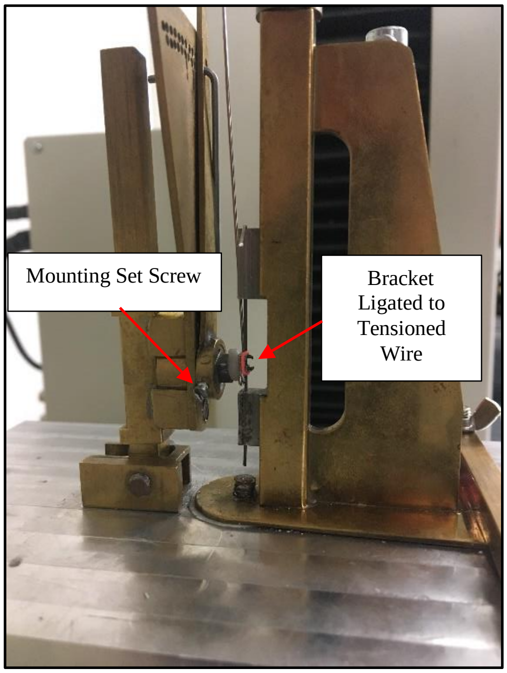

Figure 5: Jig Mounting Screw Test Stand Setup
A mounting screw is tightened for bracket setup and for each test run.

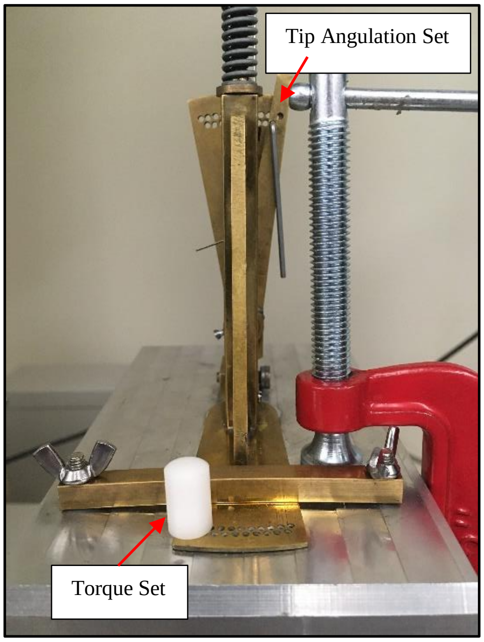

Figure 6: Jig Test Stand Angulation and Torque Setup
The torque was setup at 0 degrees and the tip angulation was initially set at 0 degrees. It is rotated 1 degree for each hole for the tip angulation plate.

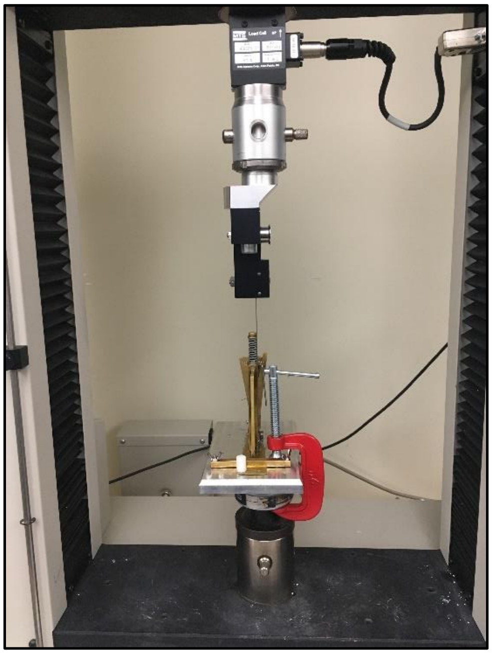

Figure 7: Overview Jig Test Stand Setup In MTS Insight 30

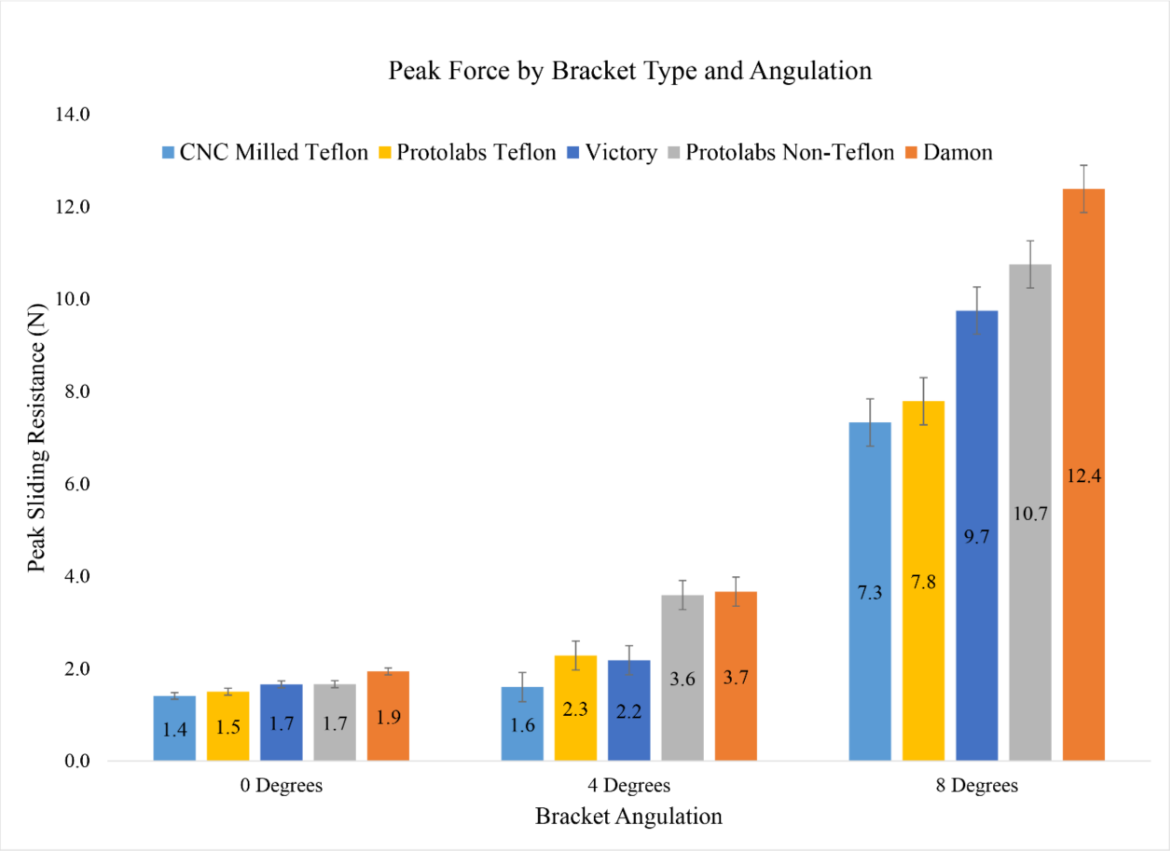

Figure 8: Bar graph of peak force mean friction
The peak force results (N) for each bracket for each angulation of tip.

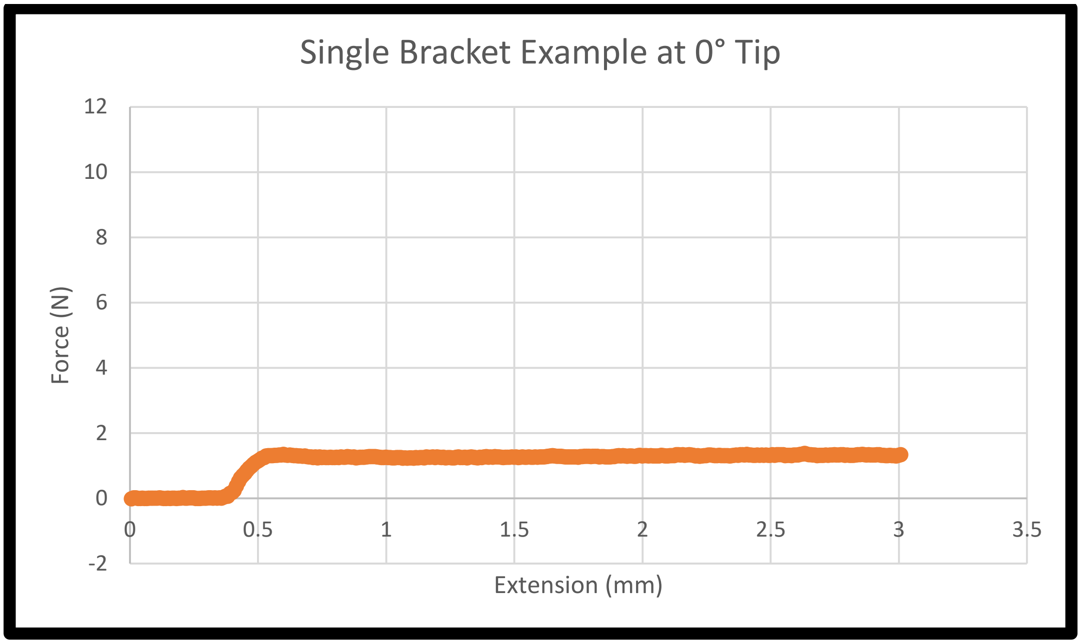

Figure 9: Teflon™ coated novel roller bracket data at 0° of tip angulation
Classic friction shows a defined peak static resistance force followed by a steady kinetic resistance force.

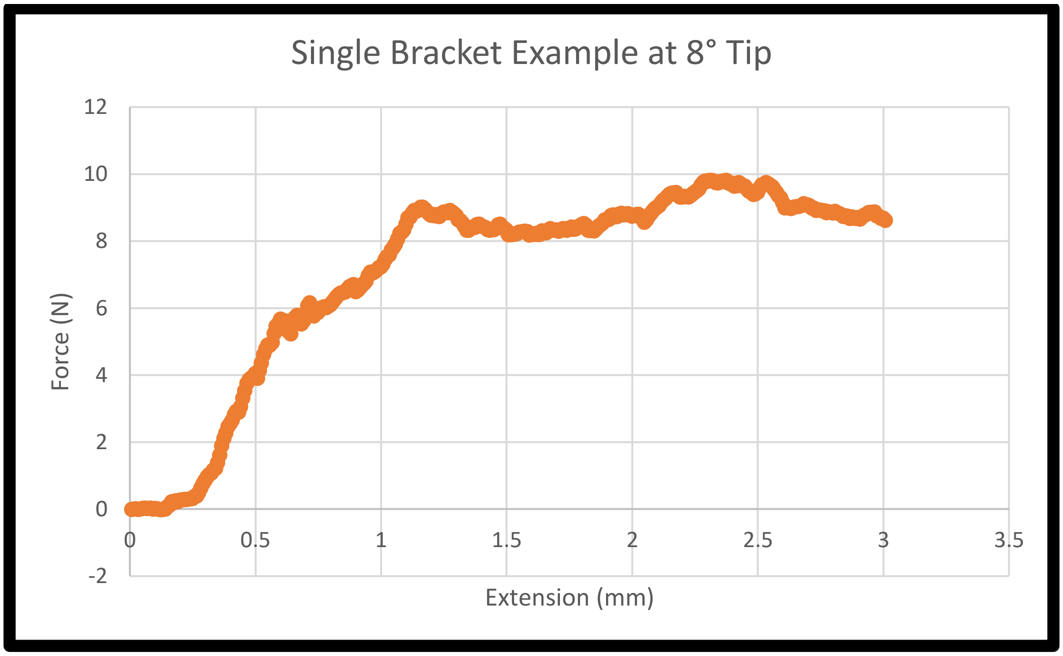

Figure 10: Non-Teflon™ coated novel roller bracket data at 8° of tip angulation
Binding and notching causes undulations in the resistance force increases as the bracket “walks” along the archwire.

Tables

Table 1: Mean Peak Sliding Force by Bracket and Angulation

Mean Friction (N)			
	0 Degrees	4 Degrees	8 Degrees
Bracket	Mean ± SD	Mean ± SD	Mean ± SD
CNC Milled Teflon™	1.41, 0.10	1.58, 0.23	7.33, 1.23
DMLS Teflon™	1.50, 0.14	2.28, 1.02	7.79, 1.73
Victory Series™	1.66, 0.14	2.18, 0.51	9.75, 0.71
DMLS Non-Teflon™	1.66, 0.46	3.59, 1.52	10.75, 1.77
Damon Q	1.94, 0.24	3.67, 1.35	12.38, 2.52

*SD = Standard Deviation

Table 2: Means and Standard Error Peak Sliding Force by Bracket and Angulation Results are Means ± standard error (Standard Error = SE).

	0 Degrees			4 Degrees			8 Degrees		
Bracket	Mean	SE		Mean	SE		Mean	SE	
CNC Milled Teflon™	1.4	0.1	a	1.6	0.3	a	7.3	0.5	a
DMLS Teflon™	1.5	0.1	a	2.3	0.3	a	7.8	0.5	a
Victory Series™	1.7	0.1	a, b	2.2	0.3	a	9.7	0.5	b
DMLS Non-Teflon™	1.7	0.1	a, b	3.6	0.3	b	10.7	0.5	b, c
Damon Q	1.9	0.1	b	3.7	0.3	b	12.4	0.5	c

*within each angulation, brackets with a different letter are significantly different (Tukey's adjusted pairwise comparisons, $p<0.05$)

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