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Ball Bearing Brackets: The game changer.

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Abstract: *Aim of the study: This experimental study was carried out to compare the behavior of ball bearing brackets with the unmodified brackets not containing ball bearing regarding the friction between the bracket and the orthodontic wire.*

Materials and Methods: *The samples consisted of 60 brackets 10 unmodified four wing brackets 10 modified four wing brackets. 10 unmodified Six wing brackets.10 modified Six wing brackets.10 unmodified passive self-ligating brackets. 10 modified passive self- ligating brackets. The details of bracket modification are still patent pending. The brackets were tested with 0.019 X 0.025 inch and 0.016 x 0.022 inch straight stainless steel wire. Static friction was measured.*

Results: *With the 0.019 x 0.025 inch Stainless Steel wire, the modified Four wing brackets showed higher static friction than the unmodified brackets. The modified Six wing brackets showed less static friction than the unmodified ones. The modified Self ligating brackets showed higher static friction than the unmodified brackets. With the 0.016 x 0.022 inch Stainless Steel Wire, The modified Four wing brackets showed less static friction than the unmodified brackets. The modified Six wing brackets showed higher static friction than the unmodified brackets. The modified Self ligating brackets showed higher static friction than the unmodified ones.*

Conclusion: *Ball bearing brackets are able to reduce friction during sliding mechanics in orthodontics.*

Key Words: *Ball Bearing Bracket, Elastic module, Friction.*

I. Introduction

In orthodontics, contact between the surfaces of the bracket-wire-ligation set produces a resistance force against the desired dental movement, called friction [1]. Friction is a force accompanying interaction of any two bodies [2]. Friction can be classified as either static or kinetic friction. Static friction is friction between two solid objects that are not moving relative to each other. Its magnitude is what is required to oppose motion up until movement starts. Kinetic friction occurs when two objects are moving relative to one another. It is usually less than static friction. Kinetic friction is less relevant to orthodontics because continuous motion along an arch-wire never occurs**.** Tooth movement occurs at approximately 1 mm per month, or 0.23×10^{-4} mm per minute making the process closer to a scenario in which static friction is more relevant [3]. In orthodontics, friction is often held accountable for slowing down the rate of tooth movement and potentially causing loss of anchorage [4]. Studies have shown that the proportion of applied force which may be lost due to resistance to sliding can range from 12 to 60%. Frictional resistance is influenced by many different factors. The force pressing the wire and the bracket surfaces together is determined by the angulation between the arch wire and the bracket slot, the size of the arch wire and the method of ligation [5].Frictional resistance to sliding arch wires against brackets can be reduced by modifying any or all of the major factors previously mentioned, but it cannot be totally eliminated. The search for a bracket system with a low frictional resistance resulted in the development of self- ligating brackets [6]. Various material compositions and properties, bracket designs and ligation methods have been investigated in an attempt to reduce friction within fixed appliances [7]. Our aim is to introduce a new orthodontic bracket that is able to reduce friction during sliding mechanics.

II. Aim of the Study

This experimental study was carried out to compare the behavior of modified brackets containing ball bearing with unmodified brackets without ball bearing regarding the friction between the bracket and the orthodontic wire.

III. Review of literature

The review elaborated different methods of canine retraction in orthodontics, types of friction, the role of friction in orthodontics, the effect of ball bearing on friction and the previous studies on friction in orthodontic literature.

3.1. Canine Retraction in Orthodontics

Two main canine retraction mechanics were known; Friction (sliding) mechanics or frictionless (sectional) mechanics. The friction created between arch wire and bracket when pulling the canine distally using sliding mechanics may be influenced by many factors. Among those factors; surface conditions of arch wire and bracket slot, wire section, torque at the wire bracket interface, type and force of ligation, use of self-ligating brackets, inter-bracket distance, saliva, and influence of oral functions [2].

3.2. Types of Friction

Friction between solids was classified into three types: static, sliding (kinetic), and rolling. Static friction included all cases in which the frictional force is sufficient to prevent relative motion between surfaces. Sliding friction, or kinetic friction, occurs when there is relative sliding motion at the interface of the surfaces in contact. Rolling friction occurs when one surface rotates as it moves over another surface but does not slip or slide at the point or area of contact. Rolling friction, such as occurs between a train wheel and a rail is attributed to small local deformities in the contact region. This type of friction is somewhat difficult to analyze [8].

3.3. Friction in Orthodontics

The portion of the applied force lost because of the resistance to sliding can range from 12% to 60%**.** Friction is not likely to be eliminated from materials, thus the best solution is to control friction by achieving two clinical objectives: maximizing both the efficiency and the reproducibility of the orthodontic appliances [9].

It has been estimated that half of the applied orthodontic force is dissipated due to friction, so that the total force applied to orthodontic brackets has to be twice that needed to produce an effective force in the absence of friction [5].

3.4. Ball Bearings

Bearings are machine elements that allow components to move with respect to each other. Accordingly, bearings permit machine parts to rotate or move in a straight line relative to one another free of the friction created by rotational or linear motion. They are used in various applications including airplanes, automobiles, machine tools, precision instruments, household appliances, none of which could operate effectively or efficiently without them. The purpose of a ball bearing is to reduce friction and to support radial and axial loads. There are four main parts of a ball bearing: two grooved, ring-like races or tracks, a number of hardened steel balls and a cage to separate and guide the balls [10].

3.5. Experiment Design and Setup

Investigations on friction can be divided into four main categories according to the type of set-up used**:**

1-Archwires sliding through contact flats, limiting the studies to the influence of materials only.
2- Arch-wires sliding through brackets parallel to bracket slot, allowing the analysis of the influence of material, bracket design and wire dimension in addition to impact of saliva and different types of ligation.
3-Archwires sliding through brackets with different second and third order angulations allowed the study of the influence of the variation between brackets.
4-Study designs in which the brackets were allowed a certain freedom of tipping simulating the impact of the biological resistance to tooth movement. [11].

IV. Materials and Methods

The samples consisted of 60 brackets. The sample was divided into six groups. Each group consisted of ten brackets. The first group consisted of 10 unmodified four wing brackets (Twin Bracket, ORMCO, USA). The second group consisted of 10 modified four wing brackets (Twin Bracket, ORMCO, USA). The third group consisted of 10 unmodified Six wing brackets (Synergy, Rocky Mountain, USA). The fourth group consisted of 10 modified Six wing brackets (Synergy Rocky Mountain, USA). The fifth group consisted of 10 unmodified passive self- ligating brackets (Damon mini 2000, ORMCO, USA). The sixth group consisted of 10 modified passive self- ligating brackets (Damon mini 2000, ORMCO, USA). All the brackets were 0.22 x 0.28 Inch slot size. All the brackets had a Roth prescription slot design. All the brackets were for the upper right canine.

Figure (1) sample of the modified brackets with ball bearings in place

Each one of the modified brackets received two ball bearings of standardized size, shape and manufacturing material. The details of the modification are still patent pending.

The wires used during the test were 0.019 X 0.025 straight stainless steel orthodontic wire (ORMCO, USA) and 0.016 x 0.022 straight stainless steel orthodontic wire (ORMCO, USA). New elastic module of the same size and type (Hubit, Korea) was used with each bracket during the test.

60 acrylic blocks of standardized size and shape were manufactured from chemical cured acrylic resin (Acrostone) to act as carrier for the brackets during the test. Each acrylic block was 15 mm in width so all the blocks could fit into the testing machine. Each Acrylic block had a width of 15 mm. Measurements were held accurately so that each bracket was cemented exactly at the center of the width of the acrylic block for standardization

A custom made metallic bar 10 cm in length and of a square cross section (10 mm each side) was manufactured. Three lower incisor brackets (Ormco, Roth prescription, slot 0.022 inch) were adhered to the metallic bar to secure the position of the wire during the test. Lower incisor brackets were selected because they have zero tip.

Universal testing machine (Lloyd LR 5 KN, Lloyd instruments, England) was used for all the samples. The software used was Nexygen.

The apparatus was assembled as follows. Each stainless steel wire was cut into segments of 5 cm length each. The end of each wire was bent to a 90 degree angle to prevent its slippage during traction of the wire. Each wire was fixed to the manufactured metallic bar using three elastic modules of the same type used for fixation of the bracket to the wire. Each acrylic block with its bracket was attached to the unmovable part of the testing machine. Each bracket was fixed to the wire using a new elastic module (Hubit, Korea) directly from the packet. Elastic modules were used to prevent individual differences in forces resulting from the ligature wire. A new wire was used with each bracket to make sure that any change in surface characteristics of the wire after testing will not affect the results. Each bracket

was tested twice, once with the 0.019 x0.025 stainless steel wire and once with the 0.016 x0.022 Stainless steel wire.

Figure (2) Lloyd universal testing machine in place

All the tests were performed under dry conditions at room temperature. Each wire was pulled through the bracket at cross speed of 5 mm/min for 5 mm distance for each wire. The force was measured in gram force. Static friction was measured.

The data got extracted from the Lloyd machine in the form of readings of load along the extension moved by the bracket. Excel program was then used to form a graph.

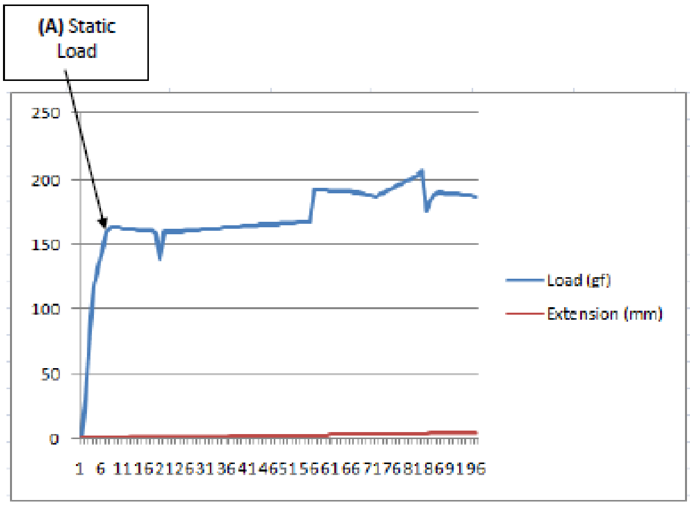

Figure (3) graph of static load.

The graph was then used to extract the Static load. The static load was that point where the bracket overcome the resistance and started to move represented by point **(A)** on the graphas shown in fig. 3.

In an attempt to obtain statistically reliable results the sample size of 60 brackets which was found to be statistically reliable was selected according to a post hock statistical power analysis. Power analysis was performed to study power (N=60), the effect size (ES) in the study was 0.5, considered to be large using cohen's (1988) criteria. With an alpha power > 0.95, (G Power 3.1.).

Statistical analysis was performed by Microsoft Office 2013 (Excel) and Statistical Package for Social Science (SPSS) version 20. Data were presented as mean and standard deviation (SD) values. The significant level was set at $P \leq 0.05$. Kolmogorov-Smirnova and Shapiro-Wilk tests was used to assess data normality and data was assumed normally distributed.

Factorial ANOVA was used to assess effect of modification bracket and wire over friction. Simple main effect with bonferrioni correction was used if the ANOVA was significant.

V. Results

Table (1) Mean, standard deviation and number of samples of different wires and brackets with and without bracket modification. Static Load.

Descriptive Statistics[a]

Dependent Variable: friction

Wire	Bracket	modification	Mean	Std. Deviation	N
0.019*0.025	Four Wing	Unmodified	167.5	7.9	10
		Modified	170.3	20.0	10
	Six Wing	Unmodified	128.2	13.7	10
		Modified	46.7	16.7	10
	Self- ligating	Unmodified	16.3	4.8	10
		Modified	499.3	18.0	10
0.016*0.022	Four Wing	Unmodified	147.9	4.8	10
		Modified	66.8	5.8	10
	Six Wing	Unmodified	45.1	3.0	10
		Modified	103.6	9.3	10
	Self –ligating	Unmodified	11.6	2.9	10
		Modified	24.7	2.3	10

As shown in Table 1, each group consisted of 10 brackets. With the 0.019x0.25 wire, the unmodified Four wing brackets showed static friction with a mean of 167.5 gram of force. The modified Four wing brackets showed static friction with a mean of 170.3 gram of force. The unmodified Six wing brackets showed static friction with a mean of 128.2. The modified Six wing brackets showed static friction with a mean of 46.7. The unmodified Self-ligating brackets showed static friction with mean of 16.3. The modified Self-ligating brackets showed static friction with mean of 499.3.

With the 0.016x0.022 wire, the unmodified Four wing brackets showed static friction with a mean of 147.9 gram of force. The modified Four wing brackets showed static friction with a mean of 66.8 gram of force. The unmodified Six wing brackets showed static friction with a mean of 45.1. The modified Six wing brackets showed static friction with a mean of 103.6.The unmodified Self ligating brackets showed static friction with mean of 11.6. The modified Self ligating brackets showed static friction with mean of 24.7 gram force.

Table (2): Mean, standard of error, confidence interval and *P* value of different wires and brackets with and without modification. Static Load

Wire	bracket	modification	Mean	Std. Error	*P* value
0.019*0.025	Four wing	Unmodified	167.500	2.52	0.566
		Modified	170.333	6.35	
	Six wing	Unmodified	128.225	4.33	<0.001
		Modified	46.754	5.29	
	Self- ligating	Unmodified	16.363	1.52	<0.001
		Modified	499.391	5.7	
0.016*0.022	Four wing	Unmodified	147.980	1.52	<0.001
		Modified	66.862	1.83	
	Six wing	Unmodified	45.145	0.94	<0.001
		Modified	103.608	2.96	
	Self -ligating	Unmodified	11.646	0.93	0.009
		Modified	24.782	.075	

When the brackets were measured with the 0.019X0.025 stainless steel wire. The four wing modified brackets showed higher static load than the unmodified four wing brackets. The increase was of no statistical significance (*p* Value = 0.566).The Six wing modified brackets showed less static load than that of the Six wing unmodified brackets, The decrease was of statistical significance (*p* Value <0.001). The self-ligating modified brackets showed higher static load than the unmodified Self ligating brackets, the increase was of a statistical significance (*P* value <0.001).

When the brackets were measured with the 0.016 x0.022 stainless steel brackets. The Four wing modified brackets showed less static load than the four wing unmodified brackets, the decrease in static load was of statistical significance (*P* Value <0.001).The Six wing modified brackets showed higher static load than the Six wing unmodified brackets, The increase in static load was of a statistical significance (*P* value <0.001). The modified self-ligating brackets showed higher static load than the unmodified Self ligating Brackets, the increase in the static load was of statistical significance (P value =0.009).

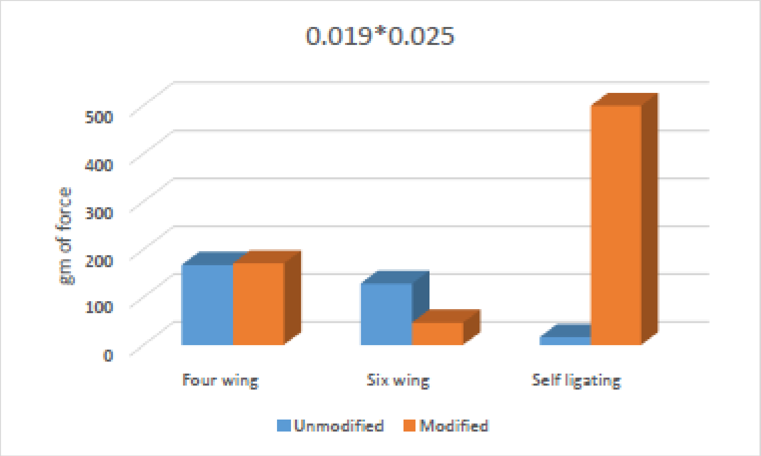

Figure (4): Mean of static load of different brackets with 0.019x0.025 wire.

According to fig. 4, when the brackets were measured with the 0.019X0.025 Stainless steel wire. The four wing modified brackets showed higher static load than the unmodified four wing brackets, The increase was of no statistical significance (*P* Value = 0.56).The Six wing modified brackets showed less static load than that of the Six wing unmodified brackets, The decrease was of statistical significance (*P* Value <0.001). The self-ligating modified brackets showed higher static load than the unmodified Self ligating brackets, the increase was of a statistical significance (*P* value <0.001).

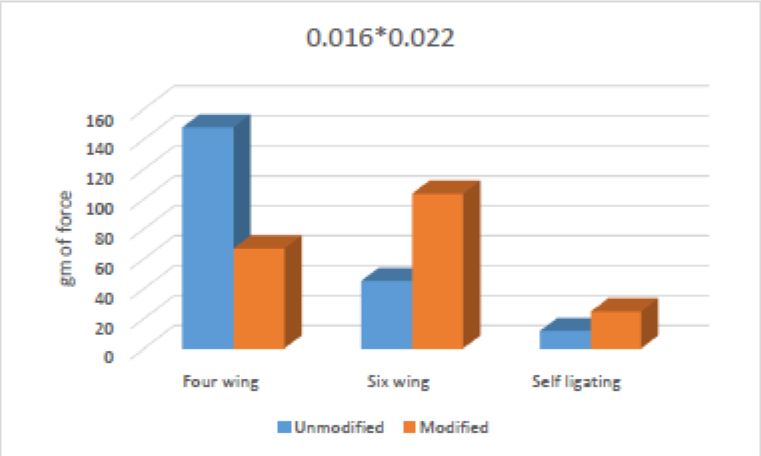

Figure (5): Mean of Static Load of different brackets with 0.016x0.022 Wire.

According to fig. 5, when the brackets were measured with the 0.016 x0.022 stainless Steel brackets. The Four wing modified brackets showed less static load than the four wing unmodified brackets, the decrease in static load was of statistical significance (*P* value <0.001). The Six wing modified brackets showed higher static load than the Six wing unmodified brackets, The increase in static load was of a statistical significance (*P* value <0.001). The modified self-ligating brackets showed higher static load

than the unmodified Self ligating Brackets, the increase in the static load was of statistical significance (P Value = 0.009).

VI. Discussion

Since 1930 onwards, extraction treatment has gained massive interest and popularity, with the premolars being considered as the choice of extraction followed by canine retraction [5]. Orthodontic space closure should be individually tailored based on the diagnosis and treatment plan. The selection of any treatment mechanism, involving any technique, stage, spring or appliance design, should be based on the desired tooth movement. Consideration of the force system produced by an orthodontic device aids in determining the utility of the device for correcting any specific problem. [12].

6.1. Choice of the Brackets

It is important to control classical friction in order to identify the real magnitude of orthodontic forces delivered to the periodontium, increasing reproducibility in sliding mechanics [13]. The mechanisms normally associated with classical friction control are self-ligating brackets, which eliminate the need for elastomeric or steel ligatures to hold the orthodontic arch wire in the slot [14].

The term self-ligation in orthodontics implies that the orthodontic bracket has the ability to engage itself to the arch wire and is therefore able to reduce friction by eliminating the ligation force. These bracket systems have a mechanical device built into the bracket to close off the edgewise slot. Two types of self-ligating brackets have been developed: those that have a spring clip that presses against the arch wire and those in which the clip just closes the slot and does not actively press against the wire [15]. In our study we used the passive type of self- ligating brackets.

Classical friction can also be controlled with special brackets that allow one to seat the orthodontic arch wire actively or passively according to the insertion site of conventional elastomeric ligatures. An example of special brackets is the Synergy orthodontic appliance, manufactured by Rocky Mountain Orthodontics. Synergy features six tie-wings instead of the four present in twin brackets. For a passive system, one should place a conventional elastomeric ligature under the central tie-wings only, so that the ligature remains supported on the lateral extensions of the central tie-wings. When an active system is desired, a conventional elastomeric ligature is placed under the lateral tie-wings. In this configuration the ligature is made to rest on the orthodontic arch wire, compressing it against the bottom of the slot. [14].

Our study was done on three types of brackets, Four wing brackets, Six wing brackets and Self ligating brackets. Two brackets were designed by manufacturer with the aim of friction reduction between bracket and wire which are the Six wing and Self ligating brackets according to *[16]*. The third type selected was the traditional four wing as a gold standard.

Upper right canine brackets were selected for standardization between the samples. For the purpose of standardization all the brackets were 0.22 x 0.28 inch slot size and had a Roth prescription slot design.

6.2. Choice of the wire

The end result of space closure after extraction should be upright, well-aligned teeth with ideal root angulations and positions. This implies that the tooth movement will almost always require some degree of bodily tooth movement or even root movement. Translation of a tooth takes place when the root apex and crown move the same distance and in the same horizontal direction. The center of rotation is infinitely far away. A horizontal force applied at the center of resistance of a tooth will result in this movement. However the point of force application at the bracket is far away from the center of resistance thus the moment/force ratios acting on anterior and posterior teeth should approximate 10/1, which is the ratio needed for bodily tooth movement [12].

Using undersized arch wires in edgewise brackets is a way to decrease friction if teeth are to slide along the arch wire. Sliding teeth along an arch wire requires at least 2 mil of clearance, and even more clearance is better [5].

In a study performed to evaluate the mechanical behavior of different devices for canine retraction they found that with smaller wires (0.018 in) the canines underwent more distal tipping than with wires of greater dimension (0.019 x 0.025 in) and consequently greater extrusion of the incisors which may compromise esthetics with greater exposure of incisors and gummy smile. This could be justified by the greater flexibility presented by the 0.018 in Steel in comparison with 0.019 x 0.025 in steel. They concluded that thicker arch wires presented greater vertical control and less distal tipping of the canines during retraction [17].

In a study which compared the properties of stainless steel, Beta Titanium and Timolium arch wires they found that upon tensile evaluation the stainless steel was the strongest alloy. When load deflection properties were tested, Stainless Steel was the most rigid among the three arch wires with very high loading values and less spring back properties. Also, the least friction was observed with Stainless Steel arch wires. Scanning Electron Microscopy showed that Stainless Steel has an almost smooth surface which made it the mainstay arch wire in orthodontic mechano-therapy [18].

Space closure should be completed on a 0.019 x 0.025 inch arch wire before a 0.021 x 0.025 inch wire is used to complete tooth alignment [19]. The 0.016 x 0.022 stainless steel wires were used to investigate whether smaller 0.016 x0.022 wires would perform differently with the ball bearing brackets than the larger 0.019 x 0.025 wire. Thus the wires used in our study were 0.019 x0.025 stainless steel wire and 0.016x0.022 stainless steel wires

6.3. Ball Bearings

Rolling elements typically generate much less friction than sliding elements at comparable loads and speeds. For this reason, the friction contribution of roller bearings is usually insignificant in comparison with that of the contacts in a machine [20]. Bearing permits machine parts to rotate or move in a straight line relative to one another free of the friction created by rotational or linear motion. They are used in various applications including airplanes, automobiles, machine tools, precision instruments household appliances, none of which could operate effectively or efficiently without them [10].

Friction between solid bodies is an extremely complicated physical phenomenon. It encompasses elastic and plastic deformations of the surface layers of the contacting bodies, interactions with wear particles, micro-fractures and the restoration of the continuity of materials, excitation of electrons and photons, chemical reactions, and the transfer of particles from one body to the other. It is possible to formulate a very simple law for dry friction. The frictional force is proportional to the normal force and as good as independent from the speed. The property of dry friction lies in the fact that in a first order approximation, it is dependent neither on contact area nor on roughness. This property allows us to use the notion of the coefficient of friction. The coefficient of friction, however, gives only a very rough first approximation of the quotient of frictional force to normal force. Leonardo da Vinci was the first to experimentally investigate the law of friction and formulate the most important principles (e.g. that the frictional resistance is proportional to the weight and independent from the contact area [21].

The frictional force *FR* between two bodies which are pressed together with a normal force *FN* exhibit the following simple properties in a rough approximation:-

A. *Static Friction*. In order to set in motion a body lying on an even surface in a state of rest, a critical force, the *force of static friction FS* , must be overcome. This force is roughly proportional to the normal force *FN*:

$F R = \mu s F N$ (1)

The coefficient μs is called the *coefficient of static friction*. It is dependent on the pairing of the contacting materials, however, shows almost no dependence on contact area or roughness.

Kinetic Friction F R is the resisting force which acts on a body after the force of static friction has been overcome. Coulomb experimentally determined the following properties of kinetic friction:

- Kinetic friction is proportional to the normal force $F N$: $FR = \mu k F N$ (2)

It shows no considerable dependence on the contact area or roughness of the surface. What is interesting is that the *coefficient of kinetic friction* is approximately equal to the coefficient of static friction:

$\mu s \approx \mu k$ (3) [21].

It is hence concluded from the previous equations that the friction is dependent on both the normal force and the coefficient of friction of the two contacting surfaces. The normal force is simply the force formed as a reaction to the force pressing one object against the other. If an object is pressing on the floor by its weight, as a reaction the floor will apply an equivalent amount of force on the object and this is the normal force [22]. The coefficient of friction is a constant value for every two materials contacting each other.

In Orthodontics the coefficient of friction depends on the material of manufacturing of both the orthodontic bracket and the orthodontic wire and that explains why different materials produce different amounts of frictional resistance when all the other contributing factors are kept the same. The normal force in orthodontics would be the reaction to the force pressing the wire against the bracket slot base which is the force of ligation. Several attempts had been made to decrease friction through decreasing the force of ligation like self- ligating brackets and the six wing brackets .In our study we decided to reduce friction through the reduction of the coefficient of friction since the ball bearings have much less coefficient of friction than any two surfaces sliding against each other.

For ball and roller bearings operating at typical loads and speeds, the friction coefficients range between μ =0.001 and μ =0.005 [23]. While the coefficient of static friction of steel on steel was 0.74 μ and the coefficient of kinetic friction was 0.57 μ [24]. With a simple calculation we could conclude that the coefficient of classical static friction would be 740 times less and the coefficient of dynamic friction would be 570 times less if ball bearing brackets were used instead of sliding steel wire along a steel bracket base directly.

In the current study each one of the modified brackets received two ball bearings of standardized size, shape and manufacturing material.

6.4. Research design

The aim of the study was to attempt to modify bracket base design by introduction of the ball bearing concept as an added mean of friction reduction to the three types of brackets.

The angle at which the space between wire and slot disappears, known as critical contact angle, constitutes a milestone in the evaluation of classical friction because it is at this point that the contact force between arch wire and bracket slot occurs, thereby producing binding, which is incorporated into the total friction and prevents classical friction from being assessed separately [25]. For this reason, it is important to eliminate binding during mechanical tests. The second order critical angle (mesio-distal direction), between a 0.019 x 0.025-in rectangular wire and a 0.022 x 0.028-in slot bracket with a width of 3.5 mm is of approximately 1.5 degrees [26]. The greater the bracket width, the lower the second order critical angle, which increases the likelihood of binding. In classical friction tests where the arch wire is made to slide along several brackets, the second order critical angle is even smaller as the width in question corresponds to the distance between the brackets located at the ends. Therefore, even a minor misalignment between wire and slots will produce a contact between wire and bracket slots, as well as binding, which increases the total friction and prevents the measurement of classical friction separately. [25]. Thus, in order to reduce the likelihood of bias caused by binding it is convenient to use only one bracket in tests that assess the magnitude of classical friction [14].

In the setup of the testing condition the wire was attached to three brackets cemented to a custom made metallic bar to assure that the new wire used with each test will always be secured in the same place parallel to the metallic bar for reproducibility and consistency of the test condition between various brackets [27].

Each stainless steel wire was cut into segments of 5 cm length each. Although in the orthodontic literature the fixation of the wire to the brackets on the metallic bar was performed using three elastic modules only (one module for each bracket). In our test each wire received a 90 degree bend at its end to make sure the wire wont slip from the brackets on the metallic bar during performance of the test which could affect the accuracy of the experiment and jeopardize the standardization.

The test was performed under dry conditions to avoid the misleading measures obtained from the application of lubricants like natural saliva, artificial saliva or water. The literature is divided with regards to saliva's role in reducing friction between orthodontic wires and brackets. No differences were measured in friction levels between trials with saliva and those without saliva. When human saliva is present, frictional forces and coefficients may increase, decrease, or not change depending on the arch wire alloy tested [16].

Testing would be closer to an in vivo situation if the sliding velocities used were as slow as possible [16]. No difference was between velocities of o.5, 1 and 5 mm per minute. An experimental speed of 5 mm per minute was selected as faster velocities were not representative of the clinical situation. The selection of 5 mm conserves time during experimentation [28]. Thus the test speed was selected to be 5 mm per minute

During selection of the method of attachment of the wire to the brackets there were two options, the first was elastic modules and the second was stainless steel ligature wires. The stainless steel ligature wires had technical disadvantages which were that the ligature wire could be either ligated tightly or lightly affected by human variations and that could jeopardize the standardization. Thus the elastic modules were selected as a method of ligation during performance of the test since they showed less sensitivity to human variation during fixation which allowed for better standardization [29].

Each bracket was fixed to the wire using a new elastic module (Hubit, Korea) directly from the packet to make sure that all the brackets received equal ligating force avoiding the risk of force decay of the elastic module with repeated use.

6.5. Interpretation of the results:-

6.5.1. The 0 .019 X 0.025 stainless steel wire

- **Four wing brackets**

The modified four wing brackets showed higher static friction than the unmodified brackets with the 0.019 x0.022 stainless steel Wire. The increase was of no statistical significance.

These higher results could have been due to the fact that the ball bearing system occupied a space from the bracket slot which pushed the wire against the elastic module. The elastic module became more active with the presence of ball bearing than with the unmodified brackets.

The factor that aided in increasing the friction is the large size of the wire (0.019 X0.025) which allowed for only minimal play between the wire and the bracket slot.

Previous studies have established that, when clearance exists between the arch-wire and the bracket's slot walls (the passive configuration), only classical friction contributes to resistance to sliding [13].

A study attributed the differences in frictional resistance values between different ligation methods to the shapes that the O-rings formed as they passed over the arch-wires and under the brackets' tie-wings when placed in a figure-O. When clearance no longer exists (the active configuration), elastic binding additionally contributes to resistance to sliding [30].

In a study comparing frictional values of different ligation methods which included stainless steel ligature and elastic modules. It was found that the elastic modules showed higher frictional values than the steel ligature. The increase in friction of elastic modules over the stainless steel ligature was due to the stretching of module causing the normal force to increase, which in turn pushes the arch wire more firmly against the bracket slot [31].

Slide ligatures produced significantly lower levels of friction when compared with conventional elastomeric modules. This can be explained on the basis of absence of normal force pushing the wire into the slot resulting in minimum friction at bracket-wire interface [32].

- **Six wing brackets**

The modified Six wing brackets showed less static friction than the unmodified ones with the 0.019 X 0.025 stainless steel wire which is considered a success that proved the theory of ball bearing brackets could work.

This decrease in frictional resistance could have been due to the fact that the ball bearings augmented the effect of the unique features of the six wing bracket which was originally designed to reduce friction. These unique characteristics were flared mesial and distal Lead-ins and rounded slot base which aimed to decrease binding of the wire to the bracket.

Placing the ball bearing at the rounded base of the six wing bracket could have allowed the wire to move along the rotating ball and continue its journey smoothly without hitting the rounded bracket base under the pressure from the elastic module while in the case of four wing bracket with its flat base the wire hit the edge of bracket base after passing along the rotating ball. This means that the six wing bracket got the maximum benefit of the ball bearing because of its rounded base on the contrary to the four wing bracket which was deprived from this benefit because of its flat base as shown in fig.6.

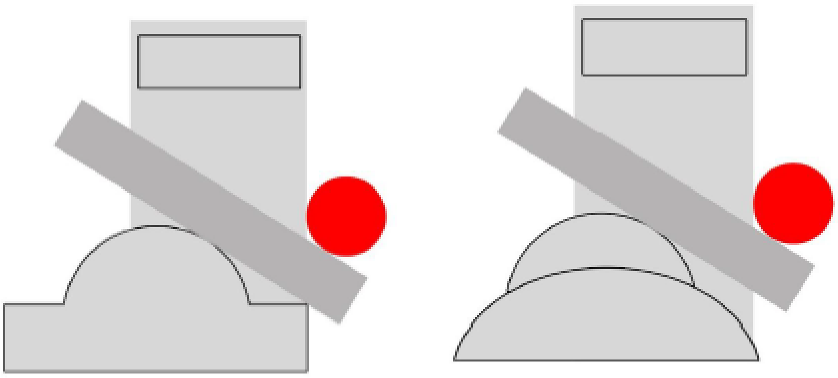

Figure (6) occlusal View of the base of four wing and six wing brackets

- **Self- ligating brackets**

The modified self-ligating brackets showed higher static friction than the unmodified brackets with the 0.019 X 0.025 stainless steel wire.

These higher results could have been due to the fact that the ball bearing system occupied a space from the bracket slot which forced the wire against the sliding door of the self-ligating brackets leading to higher friction than the unmodified brackets. The factor that aided in increasing the friction is the large size of the wire (0.019 X0.025) which allowed for only minimal play (if any) between the wire and the sliding door.

This explanation is further augmented by the fact that when we used smaller wire the increase in friction was less when compared to 0.019 x 0.025 wire.

The increase in the static and dynamic friction at the modified self-ligating brackets was much higher than that observed with the modified four wing or modified Six wing brackets because when the ball bearing system pushed the wire labially the elastic modules used with the four wing or Six wing brackets were flexible and forgiving enough to allow for the wire to protrude out and compensate for the space occupied by the balls to some extent. While with the modified self-ligating brackets the rigid locking door of the bracket didn’t allow for any labial movement of the wire. The wire was squeezed between the balls and the door leading to that dramatic increase in the friction.

A study stated that the self-ligating brackets showed higher friction than the conventional brackets ligated with stainless steel ligature when tested with wires of high dimension like 0.019x0.025 stainless steel wire [33].

6.5.2. The 0.016 x0.022 Stainless Steel Wire

- **Four wing brackets**

The modified Four wing brackets showed less static friction than the unmodified brackets with the 0.016 X 0.022 stainless steel wire.

The success of the modification to decrease both the static friction was most probably because the 0.016 x0.022 was smaller than the 0.019 x 0.025 wire which allowed for freedom of movement of the wire inside the bracket slot without being hardly pushed against the elastic module the way that happened with the 0.019 x 0.025 wire. That is another proof that ball bearing brackets could actually reduce friction.

- **Six wing brackets**

The modified Six wing brackets showed higher static friction than the unmodified brackets with the 0.016 X 0.022 stainless steel wire.

Although the modified Six wing bracket succeeded in decreasing the friction with the 0.019 x 0.025 but it failed with the 0.016 x 0.022 wire.

The increase in the friction with the 0.016 x0.022 wire is most probably due to combination of three factors:- The ball bearing system, the size of the wire and the bracket design.

Due to the small size of the wire and its ability to get twisted combined with the presence of the ball bearing at the base of the bracket (Which acted as a fulcrum point from which the wire could slip occlussally or gingivally). The slippage and twisting of the wire got it tucked in between the ball and the side wall of the bracket which led to third order binding in the system that caused this increase in the friction as shown in fig. 8. Consider a cantilever wire (like the one we used in our study) doubling the diameter of the wire increases its strength 8 times, decreases its springiness by a factor of 16 and decreases range by a factor of two. When it comes to torsion decreasing the size of a wire decreases its strength in torsion while increasing its springiness and range [5].

The slippage, twist and getting tucked didn't occur with the 0.019 x 0.25 wire because it is stiffer and larger in size allowing for minimal play between the wire and the bracket a shown in fig. 7.

A study stated that the method used to insert the wire into the Instron machine is yet another factor that can reduce the slack between the rectangular wire and the slot, thus producing binding. Wire insertion is usually accomplished by means of a latch or a vise. This maneuver, however, can twist the wire and cause third order binding (bucco-lingual direction). There is a third order critical angle between the rectangular wire and the bracket slot, a value that reflects the limit of wire rotation upon insertion of such wire in the testing machine. However, torque also affects the second order critical angle. Rectangular wire torsion increases the effective height of the rectangular wire, decreasing the slack in the slot and further reducing even more the second order critical angle, which raises the likelihood of binding **[34]**. That augments our theory.

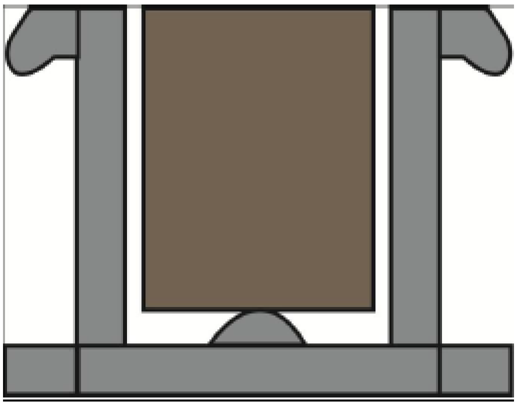

Figure (7) 0.019 x 0.025 Wire over the Ball Bearing

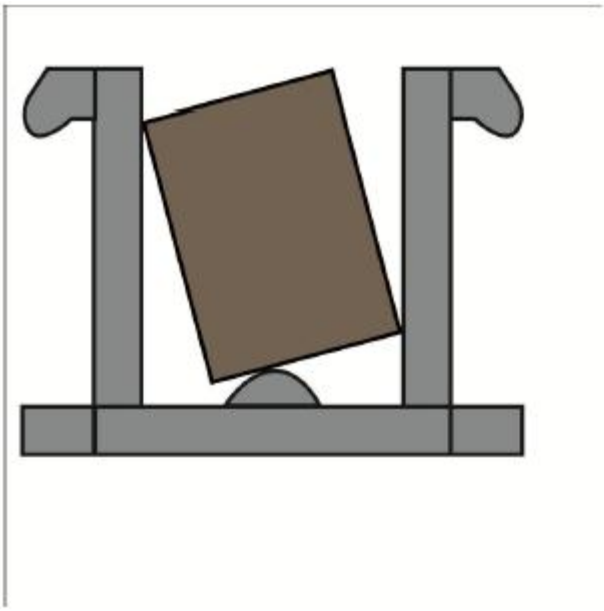

Figure (8) 0.016 x 0.022 Wire twisted causing third order binding

- **Self- ligating brackets**

The modified self -ligating brackets showed higher static friction than the unmodified ones with 0.016 X0.022 stainless steel wire.

Again, like the 0.019 x 0.025 stainless steel wire, the modified brackets showed higher static friction for the same reason. The ball bearing system occupied a space which pushed the wire against the sliding door. The rigid locking door of the bracket didn't allow for any labial movement of the wire so the wire was squeezed between the balls and the door leading to that dramatic increase in the friction. But since the 0.016 x0.022 stainless steel wire is smaller than 0.019 x0.025 the increase in the amount of friction was not that high.

A study stated that the self-ligating brackets showed higher friction than the conventional brackets ligated with stainless steel ligature when tested with wires of high dimension like 0.019x0.025 stainless steel wire [33].

VII. Conclusions

- Each type of the orthodontic brackets showed different amount of frictional resistance according to its design.
- When the balls were added to each bracket type they started to show frictional resistance values different from that of the unmodified brackets alone or the ball bearing system alone.
- Since the wire (shaft) contacts both the bracket slot walls (Housing) and the balls at the same time, a new mechanical condition was created.
- Different types of ball bearing brackets / wire combinations showed different values of static friction depending on the following factors:-

1. The original design of the bracket
2. The size of the wire used.
3. The method of attachment of the wire to the bracket (an elastic module or a sliding door).
4. The effect of adding the ball bearing to the bracket.

VIII. Future Work

We have started developing the Prototype of the Second generation of the brackets to avoid most if not all of the demerits of the first version.

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