2017

EVALUATION OF THE FRICTION GENERATED BY SELF-LIGATING AND CONVENTIONAL BRACKET-SYSTEMS IN VARIOUS BRACKET-ARCHWIRE COMBINATIONS: AN IN VITRO STUDY.

RESPICE PROSPICE

UNIVERSITY of the WESTERN CAPE

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MDS (ORTHODONTICS)

2017

APPENDIX I

EVALUATION OF THE FRICTION GENERATED BY SELF-LIGATING AND CONVENTIONAL BRACKET-SYSTEMS IN VARIOUS BRACKET-ARCHWIRE COMBINATIONS: AN IN VITRO STUDY.

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A mini-thesis submitted in partial fulfilment of the requirements for the degree of Master of Dental Surgery in the Department of Orthodontics of Dentistry, University of the Western Cape.

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November 2017

APPENDIX II

EVALUATION OF THE FRICTION GENERATED BY SELF-LIGATING AND CONVENTIONAL BRACKET-SYSTEMS IN VARIOUS BRACKET-ARCHWIRE COMBINATIONS: AN IN VITRO STUDY.

Jacqueline Renee Cupido

KEYWORDS

Friction

Ligation

Elastic Ligatures

Self-ligating (SL) orthodontic brackets

Conventional orthodontic brackets

Nickel-titanium (Ni-Ti) archwires

Stainless steel (SS) archwires

Round archwires

Rectangular archwires

APPENDIX III

ABSTRACT

EVALUATION OF THE FRICTION GENERATED BY SELF-LIGATING AND CONVENTIONAL BRACKET-SYSTEMS IN VARIOUS BRACKET-ARCHWIRE COMBINATIONS: AN IN VITRO STUDY.

J. R. Cupido

Mini-thesis, Department of Orthodontics of Dentistry, University of the Western Cape.

Background: The aim of the study is to compare the frictional resistance generated between two types of self-ligating brackets; Smart-Clip Metal SL (3M Unitek) and Damon Clear SL (Ormco), with conventional stainless steel brackets, Victory Series (3M Unitek) when coupled with various stainless steel and nickel-titanium archwires. **Materials and Methods:** All brackets had a 0.022” slot and tested using three archwires: 0.016” nickel-titanium, 0.019 x 0.025” nickel-titanium and 0.019 x 0.025” stainless steel archwires. Friction was evaluated for the upper right quadrant of the typodont. For each testing procedure, new brackets and archwire was employed to eliminate the influence of wear. **Results:** The mean results showed that the Smart-Clip self-ligating brackets generated significantly lower friction than both the Damon Clear self-ligating brackets and Victory Series brackets. However, the analysis of the various bracket-archwire combinations displayed that Damon Clear SL brackets generated the lowest friction when tested with 0.016” round nickel-titanium archwire and significantly higher friction than Smart-Clip and Victory Series brackets when tested with 0.019 x 0.025” stainless steel rectangular archwires. All brackets showed higher frictional forces as the wire size increased. **Clinical relevance:** The production of high levels of friction during orthodontic sliding mechanics presents a clinical challenge to the orthodontists. The generation of high levels of friction may reduce the effectiveness of the mechanics, decrease tooth movement efficiency and further complicate anchorage control. The amount of friction is variable in the orthodontic system and can be altered somewhat by the orthodontist’s choices.

APPENDIX IV

DECLARATION:

I declare that 'Evaluation of the friction generated by self-ligating and conventional bracket systems in various bracket-archwire combinations: An in vitro study' is my own work, that it has not been submitted for any degree or examination in any other university, and that all the sources I have used or quoted have been indicated and acknowledged by complete references.

Jacqueline Renee Cupido November 2017

Signed: ....

APPENDIX V

ACKNOWLEDGEMENTS

Foremost, I would like to express my sincere gratitude to Professor A. Harris and Professor S. Grobler for their continuous encouragement, sound advice and immense knowledge. I wish to express my gratitude to Ahmed Eldud who unreservedly helped with the statistical analysis.

Besides my advisor, I would like to thank all the Orthodontic consultants for their encouragement, insightful comments, and dedication to teaching.

I wish to thank 3M/Unitek and Ormco for supplying the brackets and archwires used in the study. I would also like to take the opportunity to thank Mr L. Rayner for all the laboratory assistance and guidance during this research project.

APPENDIX VI

DEDICATION

To

My husband

Brent Kellies, on whose constant encouragement,

emotional support and love

I have relied on through these years

My mother

Sheila Cupido, a strong and gentle soul

who taught me to trust in

God, believe in hard work and that so much

could be done with so little

My Father

Jacobus Cupido, for earning an honest living

for us and for supporting and encouraging

me to believe in myself.

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Chapter 1

Introduction

Translation of a tooth is most commonly achieved through orthodontic sliding mechanics. In this method, tooth movement can be achieved by guidance of a tooth along a continuous arch wire with the use of an orthodontic bracket (Bednar *et al*, 1991). One of the disadvantages of this mechanics is the amount of friction generated at the bracket/archwire interface, which may reduce the amount of desired orthodontic movement obtained (Bednar *et al*, 1991).

Drescher *et al* (1989) defined friction as a force that retards or resists the relative motion of two objects in contact, and its direction is tangential to the common boundary of the two surfaces in contact. Since this force works in the opposite direction to the mobile body, it is of extreme importance that the frictional forces should be minimized or eliminated when orthodontic tooth movement is being planned (Drescher *et al*, 1989).

Friction that exists before one of the objects starts to move is called static frictional force. Static friction is the amount of force necessary to start movement of an object in a static state. Kinetic friction (or dynamic friction) is the friction that exists during the movement of the object, and it is the amount of force that the object must overcome to continue moving. Static friction is proportional to the force; as the force increases, the friction also increases. When the force comes to a critical point, the static friction is overruled and the object starts to move. From this point on, resistance to movement of the object is called kinetic friction (Nanda and Tosun, 2010).

Friction between solid objects can be rolling or sliding, depending on the type of movement. Because orthodontic tooth movement is a slow process, the archwire and bracket relationship can exhibit both static and kinetic forms of sliding friction because the application of force starts a complex biomechanical relationship between the archwire-bracket-ligature-tooth-periodontium system and the alveolar bone (Nanda and Tosun, 2010).

Static or kinetic frictional forces can delay or stop tooth movement. Frictional forces are clinically unpredictable because friction is a multifactorial phenomenon. If the frictional forces exceed the force needed to move intended teeth, the latter will remain stationary and teeth that were designated as the anchor unit will move (Nanda and Tosun, 2010).

The production of high levels of friction during orthodontic tooth movement presents a clinical challenge to the orthodontists. The generation of high levels of friction may reduce the effectiveness of the mechanics, decrease tooth movement efficiency and further complicate anchorage control (Pacheco et al. 2012). One of the main goals in the search for ideal conditions for orthodontic translation is the reduction of friction at the bracket/archwire/ligature interface in certain stages of treatment (Pizzoni *et al*, 1998).

Numerous studies have evaluated factors that influence the frictional resistance between the bracket and archwire using experimental testing models (Andreasen and Quevedo, 1970; Kapilla *et al,* 1990; Cacciafesta *et al*, 2003) or a typodont (Henao and Kusy, 2005). These studies have demonstrated that the most important factors involved in the determination of the level of friction are the bracket and archwire materials, the archwire sections, the surface conditions of the archwires and bracket slots, the torque at the wire-bracket interface, the type and force of ligation, use of self-ligating brackets, interbracket distance, saliva and other oral functions (Andreasen and Quevedo, 1970; Kapilla *et al*, 1990; Cacciafesta *et al*, 2003). The amount of friction generated at the bracket-wire interface may prevent the achievement of optimal force levels in the supporting tissues. Therefore, a decrease in friction tends to benefit the hard and soft tissue response (Shivapuja and Berger, 1994).

It has been proposed that approximately 50% of the force applied to slide a tooth is used to overcome friction (Proffit, 2000). Friction, or binding, which prevents the wire from sliding through the bracket slots, can delay and even halt tooth movement.

The amount of friction is variable in the orthodontic system and can be altered somewhat by the orthodontist's choices. Thus an understanding of frictional resistance may influence their selection of wire, bracket, and type of ligation (Ehsani et al, 2009).

The primary aim of the study was to evaluate if self-ligating and conventional brackets generate equal amount of friction and how different ligation types and archwire combinations contributed to the amount of friction produced.

Chapter 2

Literature review

Various metal, ceramic or plastic brackets in combination with various archwires are utilized during fixed orthodontic treatment. The brackets have slots to allow for the seating of the archwires and tie wings to permit ligatures to attach the archwire into the bracket slots. One of the crucial objectives during orthodontic treatment is to deliver the most effective tooth movement as possible. This quest for efficiency has led to the development of various materials in orthodontics aimed at decreasing treatment time.

2.1. Friction

Besancon (1985) defines friction as the resistance to motion when one object moves tangentially against another. The normal force is the perpendicular component of the force that is acting on the contacting surfaces (Giancoli, 1980). The conventional laws of friction state that a frictional force is 1) proportional to the force normally acting on the contact, 2) independent of the area of contact and 3) independent of the sliding velocity (Tidy, 1989). When one object moves relative to another, friction at their interface produces resistance to the direction of movement.

Friction ultimately is derived from electromagnetic forces between atoms—it is not a fundamental force that can be defined independently of local conditions. It is proportional to the force with which the contacting surfaces are pressed together and is affected by the nature of the surface at the interface (e.g., rough or smooth, chemically reactive or passive, modified by lubricants) (Proffit, 2013).

Remarkably, friction is not dependent on the apparent area of contact. This is because all surfaces, no matter how smooth, have irregularities that are large on a molecular scale, and real contact occurs only at a limited number of small spots at the peaks of the surface irregularities (Proffit, 2013). These spots, called asperities, carry the entire load between the two surfaces. Even under light loads, local pressure at the asperities may cause appreciable plastic deformation of those small areas. Because of this, the true contact area is to a considerable extent determined by the applied load and is directly proportional to it. When a tangential force is applied to cause one material to slide past the other, the junctions begin to shear. The coefficient of friction then is proportional to the shear strength of the junctions and is inversely proportional to the yield strength of the materials (because this determines the extent of plastic deformation at the asperities). At low sliding speeds, a "stickslip" phenomenon may occur as enough force builds up to shear the junctions and a jump occurs, then the surfaces stick again until enough force again builds to break them (Proffit, 2013).

According to the conventional laws of friction as defined by Tidy (1989), friction arises from the force usually acting on the points of contact when a bracket is moving along an archwire. The amount of friction generated is influenced by: 1) the ligation method, and the selection of archwire at each step of the clinical procedure, 2) the rigidity of the wire and the bracket width (Andreasen and Quevedo, 1970; Frank and Nikolai, 1980) and 3) the severity of tooth malposition.

Two different types of mechanics can be employed to a achieve tooth movement during space closure. The first is the "Segmented Arch Mechanics" (SAM), which consists in bending loops on stainless steel (SS) or titanium molybdenum (TMA) wires. When Segmented Arch Mechanics is applied, the tooth or group of teeth move due to the force to moment ratio generated during the activation of the loops. Segmented Arch Mechanics is also called "closing loop mechanics" because the brackets and tubes do not slide along the archwire (Shroff et al, 1995).

Sliding Mechanics is the second type of space closing mechanics used in orthodontics, which involves the actual sliding of brackets and tubes along the wire (Staggers and Germane, 1991). Friction in orthodontics is usually associated with sliding mechanisms: an archwire moving through a bracket or a sequence of brackets. Local contact occurs between the bracket slot(s), wire and ligation as the wire slides through the sequence of brackets. Sliding Mechanics have advantages which include the use of simpler archwires, the shorter chair time and lower chances to cause patient discomfort (Ziegler and Ingervall, 1989). Nevertheless, Sliding Mechanics also presents disadvantages such as the greater chances to produce dental tipping and the friction generated at the bracket-archwire-ligature interface (Nanda and Ghosh, 1997).

During Sliding Mechanics, the application of a retraction force during space closure creates a moment on the tooth's crown that causes an initial crown tipping, followed by root uprighting later. This moment is determined by the location of the point of force application in relation to the center of resistance of the tooth or group of teeth (Pacheco *et al*, 2012). A number of successive crown tippings and root uprightings take place in the same plane of space towards the direction of the applied force. When the tooth tips, the orthodontic archwire binds against the edge of the bracket slot ("binding effect") and thereby increases the friction and further restricting orthodontic tooth movement. Greater frictional forces mean that an increased number of tipping and uprighting must take place. Thus, friction should be minimized to achieve a more efficient sliding movement of the tooth along the archwire (Pacheco *et al*, 2012).

Despite the unwanted effects that friction may produce in some stages of the orthodontic management, there are other clinical situations in which the presence of friction is useful such as when the orthodontist wants to use a group of teeth as a larger anchorage unit or during torqueing at the finishing stage of treatment (Pizzoni *et al*, 1998; Nanda and Ghosh, 1997). Therefore, a thorough understanding of how friction may impact the different clinical stages of the orthodontic treatment, the variables that increases friction and how it can be better controlled is very important to the orthodontist who wishes to improve his or her clinical skill and consistently provide better services to the patients.

2.2. Variables that may influence friction during orthodontic tooth movement

Friction may be generated by a number of factors and the amount varies depending not only on the magnitude of the force but also on the type of materials used and their surface characteristics. The amount of friction between smooth surfaces is obviously less than that between rough surfaces. However, several variables exist that can directly or indirectly contribute to the amount of friction generated (Nanda and Tosun, 2010) (Table 1). Nanda and Tosun (2010) listed them as the following:

A. Physical Factors				
Brackets	**Archwire**	**Ligature**	**Force**	**Bracket-wire angulation**
i. Material ii. Width iii. Design and manufacturing techniques	i. Material ii. Size and cross-section	i. Material ii. The use of self-ligating brackets iii. Tightness	i. Magnitude ii. Point of application	
B. Biologic factors				
Saliva		**Surrounding tissue resistance**		

TABLE 1: Variables that can directly or indirectly contribute to the amount of friction generated (Nanda and Tosun, 2010)

With so many variables affecting the frictional levels produced, it is challenging to accurately determine them in a clinical situation. The problem is further complicated by the wide selection of brackets, archwires and ligatures offered that provide a multitude of combinations for use during several stages of orthodontic treatment. No longer do orthodontists solely use the traditional stainless steel wires, brackets and ligatures. Nowadays, the uses of archwires of alloys such as cobalt-chromium (Co-Cr), Nickel-Titanium (Ni-Ti) or Beta-Titanium (B-Ti) during different stages of treatment are common (Nanda and Ghosh, 1997).

2.2.1. The effect of Bracket Material and Design.

Brackets are passive components, which deliver the means of transferring tooth moving forces from archwires, elastics and other active components of fixed orthodontic appliances (Brantley and Eliades, 2001). Brackets are manufactured from a variety of materials and they can be of various designs suitable for different orthodontic techniques. In the edgewise technique itself, there are selections in slot size, bracket width, number of wings, prescription in pre-adjusted designs, ligation capabilities and bracket material.

Stainless steel brackets seem to generate less friction than ceramic brackets when the bracket-slots and archwire are in line mesial-distally (Miura et al, 1986). When the teeth (and bracket-slots) are crooked, with archwire-slot angulations surpassing critical angles, the resistance to sliding becomes dominated by binding of the archwires in the bracket-slots. When bracket slots were angulated to the point that the engaged archwires were creating contact with diagonally opposite surface-sites within the slot, the steel bracket-slots produced more resistance than did the ceramic slots (Miura et al, 1986). In matching steel brackets produced by different overall manufacturing processes, the slot of a sintered stainless-steel bracket was found to produce 40% to 45% less frictional resistance than did that of an conventionally cast stainless-steel bracket (Griffiths et al, 2005).

Many types of aesthetic brackets have been introduced. The first plastic brackets were manufactured from unfilled polycarbonate and introduced during the early 1970’s. Unfortunately, these brackets had a tendency to undergo creep deformation when transferring torque loads generated by archwires to the teeth. However they are not preferred since they have a number of disadvantages: 1) discolouration 2) poor dimensional stability 3) bracket slots distortion and 4) generation of high amount of friction between the plastic bracket and metal archwire (Brantley and Eliades, 2001). Ceramic-reinforced, fiberglass-reinforced and metal slot-reinforced polycarbonate brackets were subsequently introduced to alleviate this problem. Another problem was discoloration of the first generation unfilled polycarbonate brackets during clinical aging (Brantley and Eliades, 2001).

Advances in material sciences and the demand for more aesthetic brackets led to the introduction of brackets made of ceramic. Ceramic brackets were introduced in 1987 and have practically replaced most other type of aesthetic brackets used today (Singh, 2007). The initially developed ceramic brackets had some shortcomings, which included – excessive bond strength (resulting in enamel fracture on debonding), brittleness of the bracket and a rough surface finish (rough finish increased friction). These have been largely addressed in the second generation of ceramic brackets and they rarely pose any problems now (Singh, 2007).

Saunders and Kusy (1994) studied the frictional characteristics of single crystal sapphire and polycrystalline alumina brackets in both the dry and the wet state in combination with four different types of archwires. Despite the difference in bracket surface roughness, no significant differences were observed in the friction between couples involving the smooth, monocrystalline versus the rough, polycrystalline samples. However the researchers concluded that the archwire alloys rather than the bracket type mostly influence the frictional resistance. Titanium wires produced higher frictional resistances than either stainless steel or cobalt-chromium wires and it was demonstrated that the presence of saliva has a tendency to decrease the friction observed between the titanium couples in each of the ceramic brackets that were tested.

Omana *et al* (1992) described that scanning electronic microscopy evaluations displayed no major surface roughness variances between the mono and polycrystalline ceramic brackets and thus concluded that this property could not be attributed as the cause for different levels of friction between the two types of brackets. The monocrystalline brackets showed a marginally smoother slot surface, but the levels of friction were very similar between the two groups (Omana *et al*, 1992).

Nishio *et al* (2004) evaluated the frictional force generated between different types of orthodontic brackets and archwires. The differences in amount of the frictional forces generated by ceramic brackets, ceramic brackets with metal reinforced slots, and stainless steel brackets in combination with stainless steel, nickel-titanium, and beta-titanium orthodontic archwires were examined. It was concluded that the stainless steel brackets had the lowest statistically significant frictional force values, followed by the ceramic bracket with metal reinforced slot. The traditional ceramic bracket showed the greatest statistically significant frictional resistance values in all tested combinations. The ceramic bracket with metal reinforced slot had a lower frictional force value than did the traditional ceramic bracket, and it seems to be a promising alternative to solve the problem of friction (Nishio *et al,* 2004). Basically, this type of bracket is intended to combine the aesthetic advantages of ceramic and the functional advantages of metal brackets. The difference in frictional force values between the ceramic bracket with metal reinforced slot and the stainless steel bracket is probably caused by the lack of a perfect adjustment and a gap between the metal slot and the ceramic bracket (Nishio *et al*, 2004). When this bracket was submitted to electronic micrograph scanning, a gap between the bracket and metal slot was observed. It occurred possibly because of the difficulty in adjusting the metal to the ceramic and the different expansion coefficients of the materials (Nishio *et al*, 2004).

Sukh *et al* (2013) tested the frictional resistance between three 0.022" orthodontic brackets: stainless steel, ceramic, and ceramic with metal slot, and different archwires combinations. The results revealed the highest mean frictional resistance with the ceramic brackets while minimum frictional resistance was found with the stainless steel brackets. The metal slot ceramic brackets generated significantly lower frictional forces than ceramic brackets, but higher values than stainless steel brackets. It was concluded that ceramic brackets with metal slot seem to be a good alternative to conventional stainless steel brackets in patients with aesthetic demands.

Williams and Khalaf (2013) evaluated the frictional resistance of 4 bracket types; self-ligating ceramic, ceramic with metal slot and module, conventional ceramic with module and conventional metal with module. The results showed that the metal bracket and metal slot ceramic bracket had lower frictional forces than the conventional ceramic bracket. The metal slot has a smoother surface than ceramic and therefore it will create less frictional resistance to sliding (Williams and Khalaf, 2013). This agrees with previous investigations that have shown frictional resistance was reduced by lining the slots of conventional ceramic brackets with stainless steel inserts (Cacciafesta *et al,* 2003; Nishio *et al*, 2004).

2.2.2. Bracket width and inter-bracket distance

Several studies claim both narrow (Frank and Nikolai, 1980; Kapilla *et al*, 1990) and wide brackets (Tidy, 1989; Bednar *et al*, 1991) produce less friction between the archwire and bracket. When a tooth tips, the normal force applied to the wire by narrow bracket wings is higher than that of wide brackets; therefore, the friction between the wire and the bracket is expected to be higher (Nanda and Tosun, 2010). The inconsistencies amongst these studies come from variances in the study designs and the materials used. The fact that the wire has more play in the bracket slot of a narrow bracket than in a wide bracket—causing less interaction between the wire and bracket—must not be overlooked. Clinically, medium or wide brackets are preferred, particularly in extraction cases where movement control in the transverse plane is important (Nanda and Tosun, 2010).

2.2.3. Ligation and ligatures

Ligation is the process by which the archwire is attached to the brackets on the teeth. Different types of ligatures have been used to hold the archwire in the bracket slot. The archwire can be ligated into the bracket slot with elastomeric ties, with stainless steel ligatures, or with self-ligating brackets which have a slot-closure incorporated into the bracket-design.

The steel ligatures are made of chrome-alloy stainless steel and their diameters vary from .009" to .012" (Zreaqat and Hassan, 2011). A forceps is used to twist these ligatures. The tightness of the steel ligatures at the bracket-archwire intersection will impact on frictional resistance. Steel ligation can therefore lead to an increase in the frictional force as different operators may use a range of ligating forces. For aesthetic purposes these steel ligatures are coated with tooth-coloured material such as Teflon. The advantages of the steel ligatures are that they do not weaken in the oral environment but maintain their shape and strength. They also provide a smaller area for the bacterial plaque to adhere to and are easier to clean than the elastomeric ligatures (Ridley *et al*, 1979). Steel ligatures are more time-consuming and tiresome to the operator and may lead to soft tissue lacerations and discomfort (Shivapuja and Berger, 1994).

Elastic ligatures are tiny rubber bands that fit around the bracket to hold the archwire in place and in the early 1970's, these elastic ties largely replaced the steel ligatures. It is easier and quicker to place these elastic bands at the bracket-archwire intersection and it could be used in chains to close small spaces or prevent spaces from opening. However, disadvantages of the elastomeric ligatures include failure to provide and maintain full archwire engagement; prevention of optimum oral hygiene; may stain permanently shortly after placement in the mouth; and deterioration of its force as constant pressure is applied to it. Friction generated by elastomeric modules may vary from 50 to 150 g (Sims *et al*, 1993). The elastic ligatures can be stretched to double their initial diameter thereby reducing the amount of friction generated (Taylor and Ison, 1996). In addition they can be used either in a figure-O pattern or in a figure-8 pattern. The figure-8 pattern ligation is beneficial to ensure full arch wire contact inside the bracket slot, but it shows significantly greater friction when compared with figure-O pattern ligation (Sims *et al*, 1993).

Various types of modules are available on the market; modules with different colours, fluoride-impregnated modules, and lubricated modules (Hain *et al*, 2003). Clear round modules produced by injection molding generate the lowest frictional forces compared with coloured, fluoride impregnated modules, and grey rectangular modules produced by cutting (Dowling *et al*, 1998). The use of lubricated modules is also associated with a reduction of frictional resistance (Hain *et al*, 2003).

Numerous studies conducted by Taylor and Ison (1996); Hain *et al* (2003) and Thorstenson and Kusy (2003) agreed that less friction is created by loosely tied steel ligatures than standard elastomeric ligatures. Some studies found no difference in the friction generated by elastomeric and stainless steel ligatures (Frank and Nikolai, 1980), while others concluded that friction caused by the elastomeric was less than that produced by steel ligatures (Ridley *et al*, 1979; Schumacher *et al*, 1990). These differences in the outcomes may be attributed to the difference in force used to tie the stainless steel ligatures. Although loose stainless steel ligatures create a lesser amount of friction compared to elastic ties, the ease and speed of the adding the elastomeric rings confirm their wide acceptance among orthodontists. In addition, the low force exerted by loose steel ligatures may be inadequate to ensure torque expression because of incomplete adaptation of the archwire inside the bracket slot (Chimenti *et al*, 2005).

2.2.4. Self-Ligating brackets

Self-ligating brackets are defined as braces which utilize a permanently installed component to engage the archwire. The cap or gate holds the archwire in the bracket slot and replaces the steel/elastomeric ligatures. Self-ligating braces may be classified into two categories: Passive and Active. These terms refer to the manner in which the brackets interact with the archwire. With the passive bracket type, the clip does not press against the archwire while with the active type the spring clip impinges on the slot from the buccal aspect and presses against the archwire.

The popularity of self-ligating brackets, which comes in different varieties, is increasing. Self-ligating brackets were introduced as a Russell attachment in 1935 with the Speed bracket (1980) followed by the Time bracket (1994), Damon SL (1996), the Twinlock (1998), the In-Ovation and Damon II brackets (2000). A study performed by Loftus *et al* (1999) indicated that the type of material of the bracket slot(s) influences the amount of friction generated when used with different bracket-archwire combinations. The study showed an increased amount of friction generated with the use of ceramic slots self-ligating brackets compared to stainless steel slots self-ligating brackets.

A study performed by Cacciafesta *et al*, (2003) determined that less friction was produced by the stainless steel self-ligating brackets compared to the polycarbonate self-ligating brackets and regular stainless steel brackets. It showed higher friction when coupled with the beta-titanium than the nickel-titanium and stainless steel archwire, with no substantial differences between the latter two. The friction was also greater with the rectangular archwire than with small round archwires for all the different bracket types and this is in agreement with Tecco *et al* (2007) and Tecco *et al* (2011). It appears that the amount of friction increases as the wire size increases irrespective of the type of bracket.

An *in vivo* study by Eberting *et al* (2001) showed mixed results with regards to the clinical efficiency between the self-ligating brackets and the conventional bracket system. It showed shortened treatment time in the cases in which the Damon self-ligating brackets were used compared with conventional brackets in which either steel or elastomeric ligatures were used.

However, Miles, (2005) detected no real extensive decrease in incisor-irregularity after twenty weeks of levelling and aligning with self-ligating Smart-Clip brackets (3M/Unitek Corporation, CA) compared to similar therapy with conventional brackets and elastomeric ligation.

Several studies have claimed a reduction in friction with self-ligating brackets and this is often cited as a primary advantage over conventional brackets (Khambay *et al*, 2004; Griffiths *et al*, 2005; Henao and Kusy, 2005;). The reason for the frictional reduction might be due to the absence of the steel or elastomeric ligatures, and it is claimed that even less friction is produced by the passive designs than active ones (Kim *et al*, 2008).

2.2.5. Archwire

The archwire is the metal wire that acts as a track to guide the teeth as they move. It is changed periodically throughout treatment as the teeth are moved to their new positions. Ideally, archwires are designed to move teeth with a light, continuous force (Proffit, 1993; Kusy, 1997). When a force is applied, the archwire must act elastically over a period of weeks to months (Kusy, 1997). Archwires come in different cross-sections (round and rectangular), sizes and material compositions.

For orthodontic treatment to be successful, clinical skills as well as the knowledge of the treatment steps and choice of materials to be used are important. One of the main elements of fixed orthodontic treatment is the choice of archwires. The aim of orthodontic management is to deliver fast and painless treatment with non-pathologic effects on tissues (Hepdarcan *et al*, 2016). There are numerous studies comparing different outcomes of several archwires and their working sequences.

Round wires are round while rectangular wires can be square or rectangular in cross section. Round wires are normally used in the early stages of orthodontic treatment, the reason being that round wires are more elastic and therefore will be able to engage all the teeth into the wire without the risk of bracket debond. After the brackets are aligned on the same vertical and horizontal plane, orthodontists usually advance to rectangular wires. The wire slot of the bracket is rectangular, therefore rectangular wire fits comfortably into the bracket. By fitting snugly into the bracket, the rectangular wire renders three dimensional control over tooth movement better than a round wire.

There is a great variation in the archwire sequence used in clinical practice, with the starting of treatment with Ni-Ti archwire followed by beta titanium or SS archwires and an average of four to five archwires per sequence being a popular choice among orthodontists (Papageorgiou *et al*, 2014). In general, the orthodontist strives to use archwires with greater stiffness and smaller range moving from the aligning phase to the working and finally the finishing phase.

There are three main types of material compositions for archwires: Stainless Steel; Nickel-Titanium (Ni-Ti); and Beta-Titanium.

In 1929, stainless steel (SS) was introduced in the field of orthodontics. It promised greater resilience than gold and it was claimed to break less likely under stress (Hepdarcan *et al*, 2016). In addition to the mechanical advantages of SS, it was cheaper than gold; therefore, it started becoming increasingly preferred. Stainless steel wires have high strength, do not rust and can be adjusted in many different ways without breaking. However, stainless steel wires are not very elastic, meaning that if you bend these wires too much, they will assume the new position and will not return to their original position. It is important for the wires to be elastic during the beginning stages of treatment, so that they can return to a predetermined U- shape and move the teeth along the wires at the same time. Compared with other archwires, these alloys apply relatively higher forces if used at the initial stage of treatment. This leads to the application of high and non-physiological forces during initial treatment even with small cross-sectioned wires. This situation necessitates making bends on wires, thus resulting in disadvantages such as increased chair time and decreased patient comfort (Hepdarcan *et al,* 2016). Therefore stainless steel wires may not be the best option during the initial stages of aligning very crooked teeth.

Stainless steel alloys are also produced in multi-stranded forms. Having multi-stranded SS is similar to having SS with loops (Kusy, 2002). These multi-stranded SS alloys offer less rigidity for the same diameter of wire. This makes these alloys possible to use even at the initial stages of treatment.

Nickel-Titanium (Ni-Ti) wires are elastic and return to their original shape when deformed. Therefore, Ni-Ti wires are frequently used in the initial stages of orthodontic treatment, to put gentle forces on the malaligned teeth. Modifications to the initial composition provided alloys, which had shape memory, elasticity and flexibility. A variation of Ni-Ti wires are heat-activated Ni-Ti (Copper Ni-Ti) wires. Heat-activated Ni-Ti wires can hold the deformed configuration at room or lower temperature, but when the wire reaches the temperature of a patient's mouth, it returns to its original shape (Pandis *et al,* 2009).

As previously mentioned, multi-stranded SS wires can also be utilized for the alignment phase of treatment (Kusy, 2002). Evans *et al* (1998) have demonstrated that these wires are just as successful as that of nickel-titanium during the initial alignment phase of treatment. Their study concluded that heat activated nickel-titanium archwires failed to demonstrate a better performance than the cheaper multi-strand stainless steel wires in a randomized clinical trial.

Beta titanium alloy, which incorporates titanium, undergoes changes when subjected to heat treatment. It is also known as beta-phase titanium alloy and usually referred to as titanium-molybdenum alloy (TMA) (Hepdarcan et al, 2016). Beta titanium alloy is rigid and can impose high force loads on teeth. However, these wires are pliable and a good choice for space closure with small bends/loops (Kusy, 2002).

Pandis et al (2009) investigated the efficiency of copper-nickel-titanium (Cu-Ni-Ti) vs nickel-titanium (Ni-Ti) archwires in alleviating crowding of the anterior mandibular dentition. The study included sixty patients. It was a single-center, single-operator, and double-blind randomized trial. Patients were treated with In-Ovation R self-ligating 0.022" slot brackets and the amount of crowding of the mandibular anterior dentition was assessed by using the irregularity index. The patients were randomly divided into 2 groups of 30 patients. One group received 0.016" Cu-Ni-Ti 35oC and the other group the 0.016 Ni-Ti archwire. All patients were followed up on a monthly basis for a period of six months. It was concluded that there was no significant difference in the alignment duration.

In another study, Mandall *et al* (2006) investigated three wire sequence patterns, which were randomly applied to patients. Group A had a sequence of conventional 0.016” nickel–titanium, conventional 0.018 x 0.025” nickel–titanium, and 0.019 x 0.025” SS wires. Group B had a sequence of conventional 0.016” nickel–titanium, followed by 0.016” SS, and finally 0.020” SS wires. Last group of the study, group C had a sequence of 0.016 x 0.022” Cu-Ni-Ti wire, followed by 0.019 x 0.025” Cu-Ni-Ti, and ending with 0.019 x 0.025” SS wire. They concluded that all sequences were equally effective. However, they mentioned that clinicians may choose a Ni-Ti sequence with the aim of reducing the number of visits to reach the working archwire. The study also determined that with the third archwire sequence (group C), severe rotations could not be solved due to the inability to engage and tie the archwire properly. Overall, these results concur with that of Tidy (1989) that the 0.016”, 0.018 x 0.025” archwire sequence is an efficient one.

Various studies have shown that the smallest amount of friction is produced by stainless steel archwires, trailed by nickel-titanium and beta titanium (Kusy and Whitley, 1990; Angolkar *et al,* 1990), while other studies did not detect any differences (Tselepis *et al,* 1994; Omana *et al,* 1992).

2.2.6. Lubrication by saliva

The result of saliva and its role as a lubricant for decreasing the amount of friction is debatable. Andreasen and Quevedo (1970) used human saliva in their study on frictional resistance and found no difference with or without saliva. They stated that the role of saliva was insignificant. Kusy *et a1* (1991) tested the use of human saliva in their experiments on frictional resistance. They reported that saliva only decreased friction with (beta-titanium and nickel-titanium (Ni-Ti) archwires. The levels registered for stainless steel and chrome-cobalt wires were higher than those obtained in dry state.

2.3. Synopsis of Literature Review

Different procedures have been used to assess the frictional force between the bracket and archwires. The prototypes used in some studies may not precisely replicate the clinical condition. Orthodontic forces are typically applied at some distance from the centre of resistance of the teeth. The compressibility of the periodontal ligament permits the teeth to tip until contact is made between the archwires and bracket corners. Many of the research studies used a model onto which fixed brackets were attached and the archwires were pulled through the slots of the brackets (Tecco *et al*, 2007; Khambay *et al*, 2005; Cacciafesta *et al*, 2003). These models do not allow for the initial tipping of the teeth to occur. Few studies used models designed to simulate the clinical situation (Kapilla *et al*, 1990; Bednar *et al*, 1991).

Most of the studies were in agreement that lower friction was produced by self-ligating brackets when coupled with small round arch wires (Shivapuja and Berger, 1994; Cacciafesta *et al*, 2003; Henao and Kusy, 2005; Thomas *et al*, 1998). However several studies show that even though the amount of friction produced by the self-ligating was lower than that generated by the conventional brackets, the friction still increased as the archwire diameter increased (Cacciafesta *et al*, 2003; Tecco *et al*, 2005; Thomas *et al*, 1998). Thus, these results correspond with a number of previous studies that stated that the amount of friction increases as the wire breadth increases and that friction is usually more with rectangular wires than with round wires (Angolkar *et al*, 1990; Pizzoni *et al*, 1998).

Steel self-ligating brackets repeatedly displayed lesser friction relative to ceramic and polycarbonate conventional brackets (Loftus *et al*, 1999; Shivapuja and Berger, 1994; Cacciafesta *et al*, 2003; Griffiths *et al*, 2005). This could be due to the fact that ceramic has increased roughness and porosity, which could lead to a higher coefficient of friction compared with stainless steel (Loftus *et al*, 1999; Shivapuja and Berger, 1994). This is in agreement with other studies that verified that friction is greater with the conventional ceramic brackets compared with conventional steel brackets (Angolkar *et al*, 1990; Cacciafesta *et al*, 2003).
All the above-mentioned studies mentioned used a 0.022” bracket slot size in their research. Thus, no conclusions can be drawn regarding the effect of the bracket slot size on frictional

resistance. Though *in vitro* outcomes are handy to anticipate clinical behaviour, the clinical outcome may be different. In addition, alignment and levelling of abnormally positioned teeth, which originates as part of the initial step of orthodontic care, should be done with flexible arch wires. Hence the studies with round arch wires without malaligned teeth may not precisely replicate what truly occurs in clinical situations.

Disagreement still exists about the friction generated by large rectangular archwires. Some studies have found that with these large rectangular archwires, the friction generated by the self –ligating brackets was not lowered compared to that of the conventional brackets (Loftus *et al,* 1999; Henao and Kusy, 2005; Tecco *et al,* 2005), while others found lower friction created by the self-ligating brackets (Sims *et al,* 1993; Cacciafesta *et al,* 2003; Thomas *et al,* 1998; Franchi *et al,* 2008). Rectangular wire is frequently being used to finish the original levelling and aligning phase, express rotation control and start torque control. Rectangular wire is frequently advised for space closure (Sims *et al*, 1994), retraction and finishing (Yeh *et al*, 2007). Thus experiments involving rectangular arch wires should if possible include tipping and rotation in the analysis settings for the results to be relevant during all stages of orthodontic treatment. A minority of studies incorporated malocclusion in their trials; all concluded that an increase in the degree of malocclusion increases the friction irrespective of the bracket type or wire size (Henao and Kusy, 2005; Yeh *et al,* 2007; Kim *et al,* 2008).

It is clear that friction between archwire and bracket is multifactorial. From the outcomes of studies mentioned above, there is an agreement that frictional resistance tends to vary with the archwire size and shape, type of wire material, angulation of wire to bracket and the ligation force.

Chapter 3

Aims and Objectives

3.1. The aim

The aim of the study was to evaluate the frictional resistance generated by self-ligating and conventional stainless steel brackets when coupled with various stainless steel and nickel-titanium archwires. The hypothesis was that different bracket systems, their ligation types and archwire combinations produces insignificant frictional forces that does not negatively affect tooth movement efficiency.

3.2. Objectives

The focus of this study was to determine and compare the frictional resistance between the stainless steel self-ligating-, the aesthetic self-ligating- and conventional brackets using different bracket-archwire combinations. These combinations included:

3.2.1. Stainless steel self-ligating brackets with:

a) 0.016” nickel-titanium round archwires,
b) 0.019 x 0.025” nickel-titanium rectangular archwires, and
c) 0.019 x 0.025” stainless steel rectangular archwires.

3.2.2. Damon Clear self-ligating brackets with:

a) 0.016” nickel-titanium round archwires,
b) 0.019 x 0.025” nickel-titanium rectangular archwires, and
c) 0.019 x 0.025” stainless steel rectangular archwires.

3.2.3. Conventional stainless steel brackets with:

a) 0.016” nickel-titanium round archwires,
b) 0.019 x 0.025” nickel-titanium rectangular archwire, and
c) 0.019 x 0.025” stainless steel rectangular archwires.

Chapter 4

Materials and Methods

4.1. Materials

Identical upper typodont models with all the teeth in alignment (no malocclusion) were fabricated. A template according to the guidelines for the placement of each bracket on each tooth was constructed (addendum A). This template was used to standardize the mounting of all the brackets on each of the typodont models. Three types of maxillary upper brackets were tested: Smart-Clip Self-ligating (d), Conventional Victory Series (d) and Damon Clear Self-ligating (c) brackets (Table 2). Three different sections of orthodontic archwires which represent the alloys used in various stages of orthodontic treatment were selected. All brackets used had 0.022" slot sizes and were tested using three archwires: 0.016" Ni-Ti (d), 0.019 x 0.025" Ni-Ti (d) and 0.019 x 0.025" SS (d). This was done for 10 non-repeated evaluations for each bracket-wire combination. A total of 90 bracket-wire samples were therefore tested.

FIGURE 1: Typodont with Smart-Clip Stainless Self-ligating Brackets cemented onto the model.

FIGURE 2: Conventional Stainless Steel Brackets fixed onto the typodont.

FIGURE 3: Damon Clear Self-Ligating Brackets fixed onto the typodont.

FIGURE 4: Three sections of archwires used: 0.016" Ni-Ti, 0.019 x 0.025" Ni-Ti and 0.019 x 0.025" SS.

The Smart-Clip Passive Self-Ligating and the Victory Series Conventional Metal Brackets were manufactured by 3M Unitek. Ormco was the supplier of the Damon Clear Passive Brackets. All Wire alloy sections were supplied by 3M Unitek (Table 2).

TABLE 2: List of Brackets (Self-ligating and Conventional), Archwire sections and Manufacturers.

Brackets	Features	Wire alloy sections	
Smart-Clip [d]	Passive Self-ligating	0.016" Ni-Ti [d] 0.019 x 0.025" Ni-Ti [d] 0.019 x .025" SS [d]	a) Bracket slot has a nominal slot dimension of .022" b) Transbond™ XT Light Cure Adhesive, 3M Unitek c) Ormco d) 3M Unitek e) Acrylic Typodonts
Victory Series [d]	Conventional SS	0.016" Ni-Ti [d] 0.019 x 0.025" Ni-Ti [d] 0.019 x 0.025" SS [d]	
Damon Clear [c]	Passive Self-ligating	0.016" Ni-Ti [d] 0.019 x 0.025" Ni-Ti [d] 0.019 x 0.025" SS [d]	

Transbond™ XT Light Cure Adhesive (3M Unitek) was used to mount the brackets from the 1st central incisor to the 2nd premolar with aid of the template.

FIGURE 5: Transbond Adhesive used to mount the brackets with aid of the template onto the typodont.

4.2. Methods

4.2.1. Fabrication of the Acrylic Typodonts

An upper silicone mould was selected from the University of the Western Cape Dental Laboratory. The mould had all teeth arranged in an ideal occlusion with no crowding, spacing or rotations. White Orthocryl Orthodontic Acrylic (Dentaurum) was prepared and poured into the silicone mould. Orthocryl is a cold-cure acrylic resin consisting of a monomer (liquid, methyl methacrylate) and a polymer (powder, polymethyl methacrylate). A doughing technique was used to mix the resin in a ratio of 2.5 parts of powder to 1 part of liquid in a silicone mixing bowl. The mix was well spatulated and vibrated for 1 minute to remove all air bubbles. The mixture was then poured into the silicone mould. The mould was placed in a pressure pot with a water temperature between 35-45ºC for 25 minutes according to manufacturer's instructions (Dentaurum instruction manual).

4.2.2. Bracket Positioning

A thin layer of separator material was brushed over the cast teeth surfaces before bonding of the brackets took place. The height and width of the central incisor of the acrylic typodont was measured. The measurement was divided in half and the bracket was bonded in the centre of the tooth. The recommended bracket-positioning chart (Addendum A) according to the MBT appliance bracket placement guide (McLaughlin *et al*, 2001) was used to position and bond all the brackets in the upper first quadrant from the first central incisor to the 2nd premolar.

4.2.3. Fabrication of the template

Once the brackets were mounted onto a typodont, the template was constructed. The Mini-Star S Dental Vacuum machine (Scheu Dental) and Copyplast, which is a Polypropylene, low density material, was used to make the template. The Copyplast thermoforming sheet, which had a thickness of 1mm was vacuumed over the typodont using the Mini-Star vacuum thermoforming machine. To fabricate the template, the thin sheet of thermoformable plastic was heated and then sucked down over the cast using the manufacturer's instructions. The excess plastic material was trimmed away. The remaining brackets were all bonded to the typodonts using the template as indirect bonding technique.

FIGURE 6: The Mini-Star S vacuum forming machine used to fabricate the template.

FIGURE 7: The Copyplast thermoforming sheet vacuumed over the typodont. This template was used to standardize the bracket position on all the typodonts.

4.2.4. Testing Apparatus

The frictional force was measured with the experimental model mounted on the crosshead of a Zwick testing machine with a 10 N load cell (Figure 8). The typodont was adapted to the testing machine, and the wires were pulled through the slots at a speed of 0.5mm/min. It allowed for sliding of the brackets along an orthodontic wire while recording the frictional forces in newtons (N). After each test, the testing machine was stopped, the bracket and wire assembly was removed, and a new assembly was placed. This was done for 10 non-repeated evaluations for each bracket-wire combination.

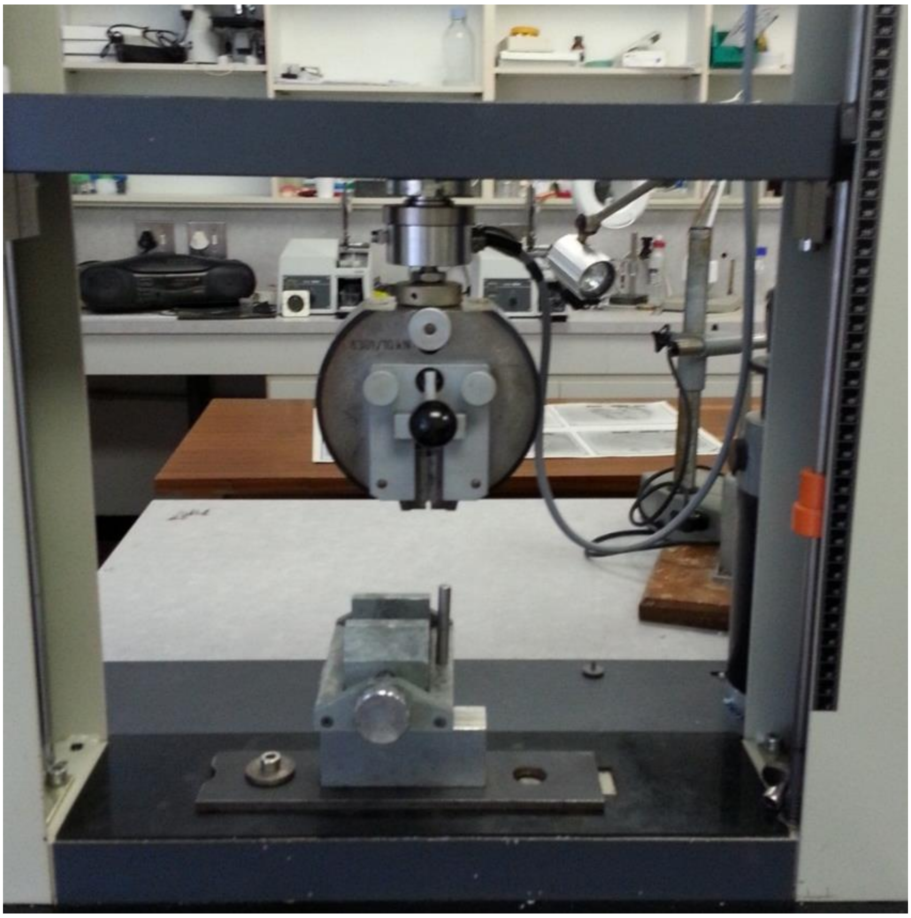

FIGURE 8: Friction Testing Apparatus: Zwick Machine

4.2.5. *Experimental Details*

All tests for self-ligating and conventional brackets were done in the dry state. Conventional brackets were ligated with elastic modules. One minute was allowed for ligation of the elastic module, followed by a three minute waiting period to allow a reproducible amount of stress relaxation to occur. Friction was evaluated for the upper right quadrant of the typodont. All wires were tested with the self-ligating and the conventional brackets.

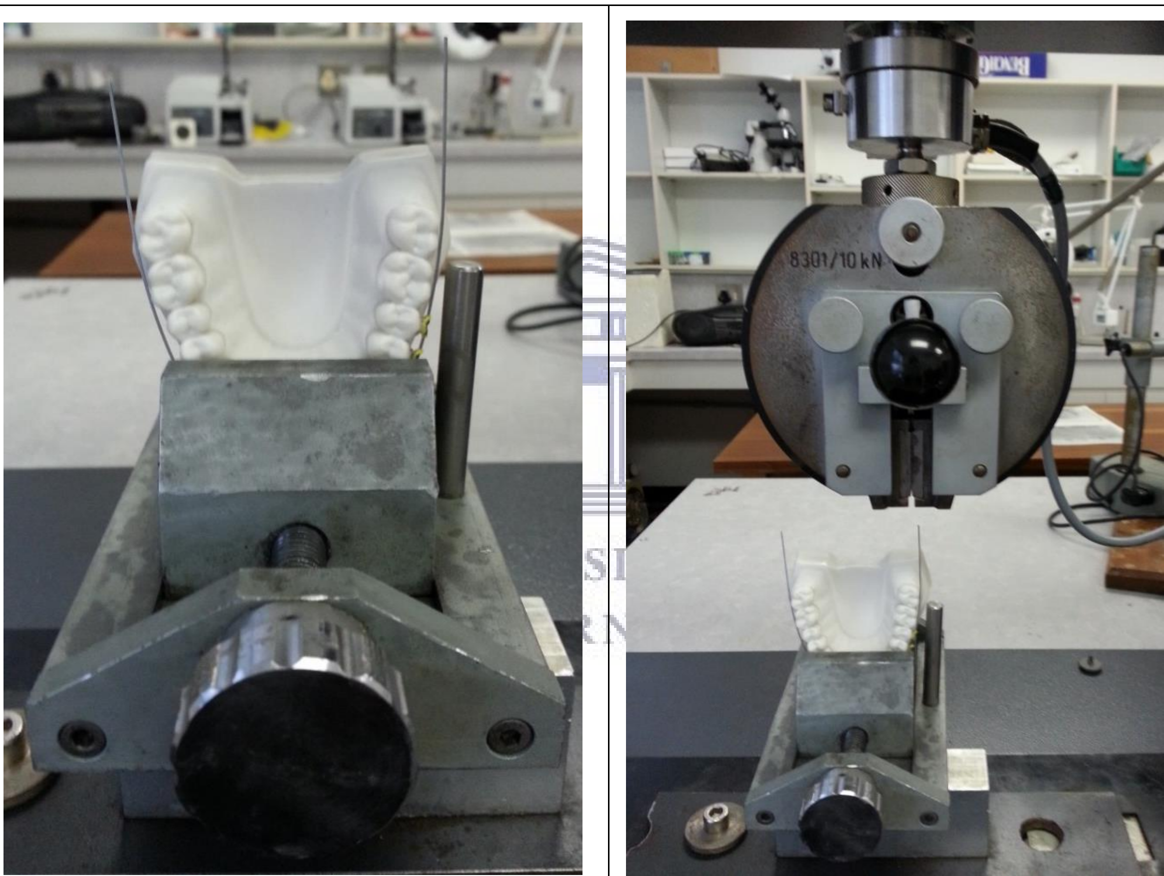

FIGURE 9: An illustration of how the study was carried out (a) typodont held in place through a pneumatic grip (b) that was mounted onto the Zwick testing machine (c) brackets mounted onto teeth from 11 to 15 (d) Archwires were gripped at the distal ends by machine.

The archwire was drawn per quadrant through the typodont model mounted with their corresponding bracket design. Once the archwires were ligated, the typodonts were vertically mounted onto the crosshead of a mechanical testing machine. The distal end of each archwire was linked to the end of an overhead load cell. Experiments were carried out in a similar manner for each of the bracket – archwire combinations as illustrated above. For each testing procedure, new brackets and archwires were employed to eliminate the influence of wear. Each bracket-archwire combination was tested 10 times therefore a total of 90 samples were tested.

4.3. Statistical Analysis

Descriptive statistics including the mean, standard deviation, and minimum and maximum values were calculated for each of the three groups of brackets and archwires. The analysis of variance (ANOVA) was used to assess whether significant statistical differences existed between the various groups. The Tukey HSD test was used for multiple comparisons between pairs at a 95% confidence interval. Significance for all statistical tests was predetermined at $P \leq .05$.

4.4. Ethical considerations

The study was conducted on typodont models. No patients were involved. However the research proposal was submitted to the Ethics Committee (UWC) prior to the commencement of this study. Approved project registration number: 12/9/10 (Addendum B).

4.5. Challenges

Typodonts were too expensive to purchase, therefore acrylic typodonts were fabricated. The fabrication of these typodonts were labour intensive and very time consuming. Due to financial constraints a lot of time was spent contacting suppliers in an attempt to get the brackets and archwires donated to complete the study.

4.6. Declaration

3M Unitek donated 150 Smart-Clip Self-Ligating and 150 Victory Series Conventional brackets. Ormco Supplied 150 Damon Clear Self-Ligating brackets. All archwires used in the study was donated by 3M Unitek (90 archwires in total which consisted of 0.016” Ni-TI (30 archwires), 0.019 x 0.025” Ni-Ti (30 archwires) and 0.019 x 0.025” SS (30 archwires). The donations of materials are independent of the study outcome and without any benefit to the donating company.

Chapter 5

Results

5.1. Brackets

Orthodontic brackets are passive components, which are cemented directly onto the teeth or welded to an orthodontic band. These attachments are used to secure the archwire into the bracket slots. Brackets are manufactured from a variety of materials available and they can be of various designs. The study evaluated the amount of friction generated when 3 types of brackets: 1) Smart-Clip Metal Self-Ligating 2) Victory Series Conventional and 3) Damon Clear Self- Ligating brackets were coupled with various archwires combinations.

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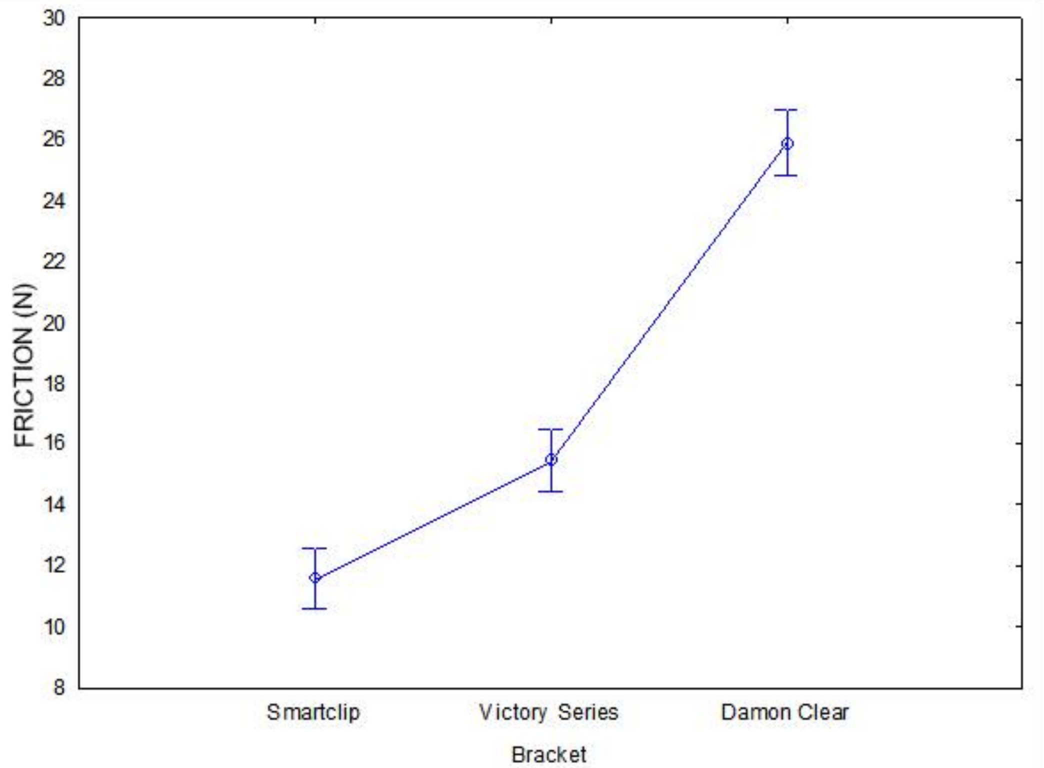

FIGURE 10: Friction generated by each bracket. The mean and standard error of each bracket demonstrated

Figure 10 indicates the mean ± standard error of the 3 types of brackets when tested with all archwires. The highest friction value was recorded by the Damon Clear Self-Ligating bracket, which was 25.915 N ± 0.549 (Addendum C4). The lowest frictional force was generated by the Smart-Clip Metal Self-Ligating bracket which was 11.596 N ± 0.496 (Addendum C4). With regard to the Metal and Clear Self-ligating Brackets, with both being passive self-ligating brackets, the result showed that the type of bracket material plays an important role in the frictional force generated.

The results of the one-way ANOVA for comparison of the mean of the 3 types of brackets (Smart-Clip Metal Self-Ligating, Victory Series Conventional and Damon Clear Self-Ligating) showed that there was a significant difference between the 3 types of brackets ($P < 0.05$) (Addendum C1). The outcome of the Tukey HSD test for pairwise comparison of the 3 bracket types (Addendum C2) indicated that all the brackets are significantly different. The test for homogenous grouping displayed that the mean of the 3 types of brackets cannot be grouped together (Addendum C3).

Since the brackets cannot be grouped together it's clear that the frictional forces generated by each type of bracket differ significantly. When sliding mechanics are employed, the frictional forces must be kept at a minimal to achieve a more efficient sliding movement of the tooth along the archwire. From the results it can be concluded that the Smart-Clip Metal Self-Ligating brackets produced the best results in terms of lowering the frictional force levels.

5.2. Archwires

Fixed orthodontic appliances (braces) consist of brackets bonded to the teeth that are connected by archwires which exert forces on the teeth. During treatment the archwires are changed periodically as the teeth adapt to their new positions in the dental arches. Ideally, archwires are designed to move teeth with a light, continuous force. Archwires are available in different cross-sections (round and rectangular), sizes and material compositions. The study evaluated the amount of friction generated when 3 archwires 1) 0.016" Nickel Titanium 2) 0.019 x 0.025" Nickel Titanium and 3) 0.019 x 0.025" SS were attached to 3 types of brackets.

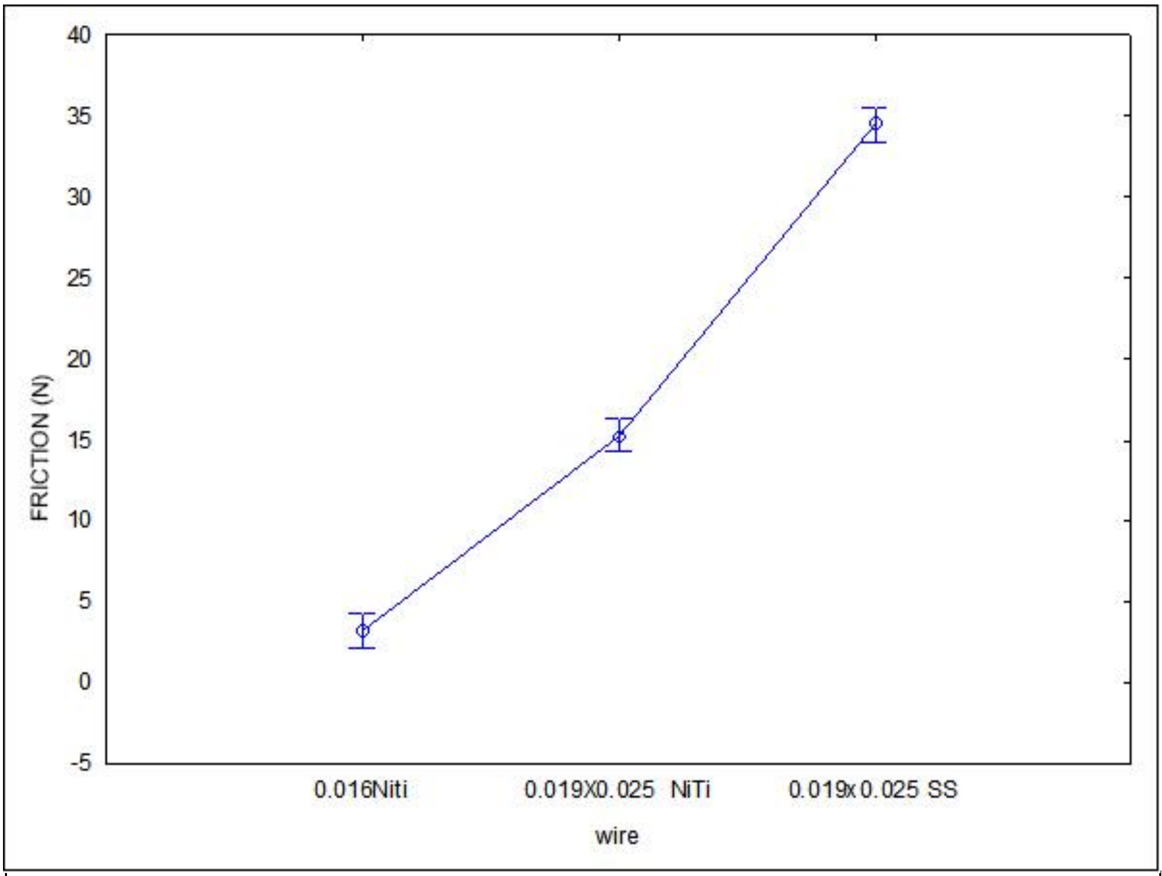

FIGURE 11: Friction generated by each archwire. The mean and standard error of each archwire revealed.

Figure 11 indicates the mean ± standard error of the 3 archwires when it was coupled with all of the brackets. Comparison of the mean of the 3 archwires (0.016” nickel-titanium, 0.019 x 0.025” nickel-titanium and 0.019 x 0.025” stainless steel) were done using the one-way ANOVA test. A significant difference were found between the 3 types of archwires ($P < 0.05$) (Addendum D1). The Tukey HSD test for pairwise comparison of the 3 archwires (Addendum D2) revealed that all the wires are significantly different and the Tukey test for homogenous grouping displayed that the mean of the 3 types of archwires cannot be grouped together (Addendum D3).

The observation of the mean values showed that the round 0.016” nickel-titanium archwire had produced the lowest forces (3.235 N ± 0.496) followed by the rectangular 0.019 x 0.025” nickel- titanium archwire (15.278 N ± 0.516) (Addendum D4). The highest frictional value was recorded with the 0.019 x 0.025” Stainless Steel archwires (34.493 N ± 0.538) (Addendum D4). It is clear from the results (Figure 11) that the archwire cross-sections (round or rectangular) as well as the archwire material contributes to the amount of friction generated.

From the results it can be concluded that the round nickel-titanium archwires are best during the initial stages of levelling and aligning since it produced the least amount of friction. The rectangular stainless steel archwires are the wire of choice for the final and finishing phase of orthodontic treatment since high amount of friction is preferred for better torque control.

5.3. Brackets and Archwires combined

The study evaluated the frictional resistance generated by self-ligating (Smart-Clip Metal and Damon Clear) and conventional stainless steel (Victory Series) brackets when coupled with various nickel-titanium and stainless steel archwires. (0.016” nickel-titanium, 0.019 x 0.025” nickel-titanium and 0.019 x 0.025” stainless steel).

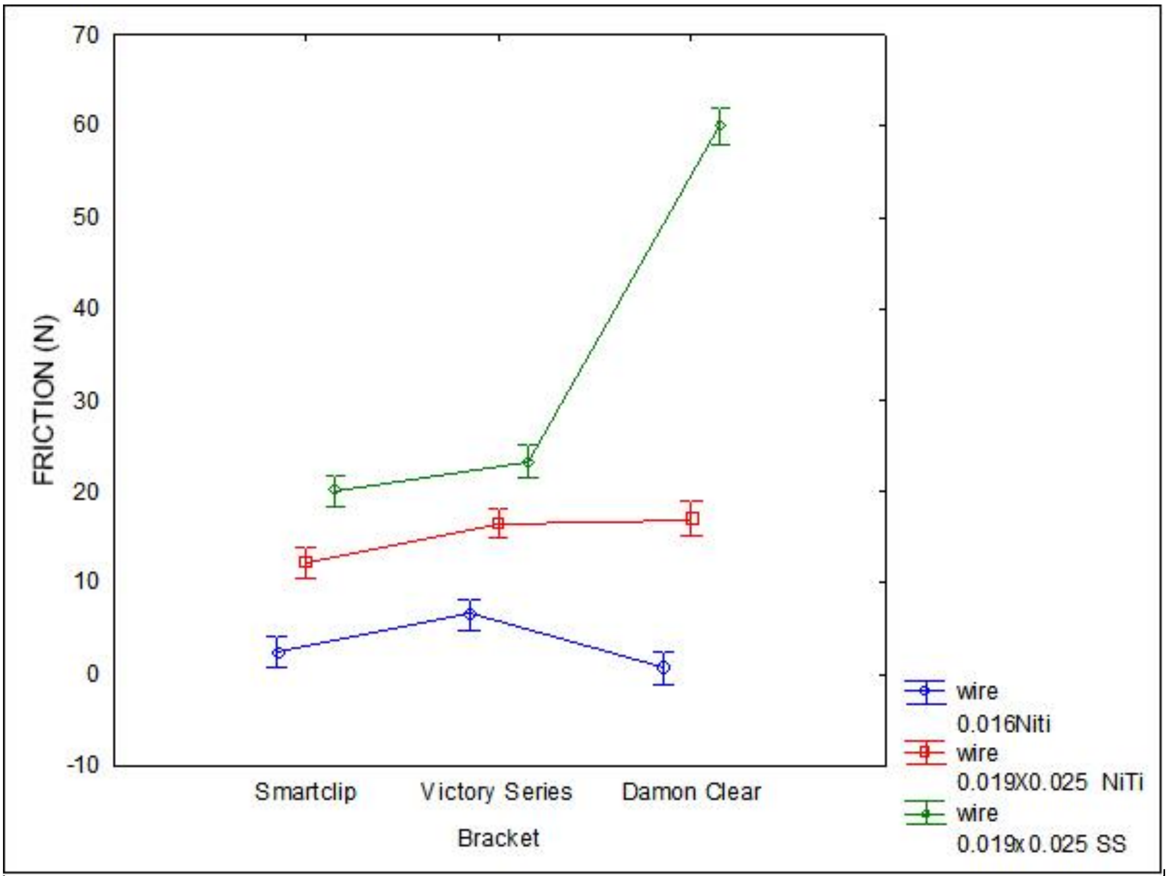

FIGURE 12: Friction of each bracket combined with each archwire. The mean and the standard error shown.

Figure 12 indicates the mean and the standard error when each bracket was coupled to each archwire. The lowest mean frictional value was recorded when the Damon Clear Self-Ligating bracket was coupled with the 0.016” Ni-Ti archwire (0.701 N) and the highest mean value was produced when the Damon Clear SL bracket was attached to the 0.019 x 0.025” stainless steel archwire (Addendum E2).

However, the Tukey HSD test for mean pairwise comparison revealed that there was no significant difference between the Smart-Clip and Damon brackets when coupled with 0.016” nickel-titanium archwire (Addendum E1). No significant difference was also found between Victory Series with 0.019 x 0.025” Ni-Ti, Damon Clear with 0.019 x 0.025” Ni-Ti and Smart-Clip with 0.019 x 0.025” stainless steel (Addendum E1). The Smart-Clip Metal self-ligating bracket produced the least amount of friction when coupled with 0. 019 x 0.025” nickel-titanium and 0.019 x 0.025” stainless steel archwires.

From the results it is clear that round archwires generate significantly less frictional forces than rectangular archwire irrespective of the bracket type.

Chapter 6

Discussion

The appropriate force applied during orthodontic treatment will lead to optimal tissue response and rapid tooth movement (Cacciafesta et al, 2003). During mechanotherapy involving movement of the wire along the brackets, friction is generated. The friction at the bracket-archwire interface might prevent getting optimal force levels in the supporting tissues (Cacciafesta et al, 2003). Therefore, understanding resistance caused by friction is important so that the appropriate magnitude of force can be used to produce optimal biologic tooth movement (Tecco et al, 2005). To understand the nature of friction between wire and bracket, several variables such as bracket material, wire alloy, and wire section should be studied.

This in vitro study was performed to investigate the amount of friction generated by Self-Ligating and Conventional bracket-systems in various bracket-archwire combinations. The amount of power (Newton) to pull an archwire through the brackets connected to a model was tested using three different types of brackets and three different sizes (diameter) of archwires. The brackets used in this study were, respectively, Smart-Clip Metal SL brackets (1), Victory Series Conventional brackets (2) and Damon Clear Self- Ligating brackets (3). The three archwire sizes used were respectively 0.016" Ni-Ti (1), 0.019 x 0.025" Ni-Ti (2) and 0.019 x 0.025" SS (3).

6.1. Comparison of conventional and self-ligating brackets

Self-ligating brackets are brackets which have a permanently installed, moveable part to entrap the archwire. Conventional brackets on the other hand require a removable component, usually elastomerics or steel ligatures to secure the archwire into the bracket slot.

As shown in the results, significant differences ($P<0.05$) existed between the Victory Series Conventional, Smart-Clip Metal SL and Damon Clear SL brackets (Figure 10; Addendum C1). The mean results presented in this study showed that the Smart-Clip Metal SL brackets produced significantly lower frictional resistance than the Conventional Stainless Steel (Victory Series) brackets and Damon Clear SL brackets (Figure 10; Addendum C4). These findings agree with the results of previous studies that found that stainless steel self-ligating brackets generated lower frictional resistance than did conventional stainless steel brackets (Shivapuja and Berger, 1994; Thorstenson and Kusy, 2001).

Similar results were found by Shivapuja and Berger (1994). They evaluated and compared five different brackets (3 metal self-ligating and 2 conventional brackets (one ceramic and one metal) using 0.018” archwire. The archwire was ligated into each bracket slot, either with 0.012” [0.30 mm] stainless steel ties or with 0.40 mm (0.106”) polyurethane elastomeric ties. They concluded that all three of the self-ligating bracket systems displayed a significantly lower level of frictional resistance compared to the conventional bracket systems. No significant difference in the amount of friction generated were found between the 3 types of self-ligating brackets.

These results are further supported by a study performed by Thorstenson and Kusy (2001). Two types of brackets were compared in this study; a conventional bracket (Mini Diamond Twin Bracket) and a self-ligating bracket (Damon SL Bracket). The brackets were coupled with 0.018 x 0.025” stainless steel rectangular archwires. The study found that the resistance to sliding of the self-ligating brackets was lower than that of the conventional brackets because of the absence of a ligation force. Kim *et al* (2008), Franchi *et al* (2008) and Monteiro *et al* (2014) further supported the findings. They reported lower friction for Smart-Clip brackets compared with conventional brackets when coupled with either round (0.014” and 0.016”) or rectangular (0.019 X 0.025”) archwires.

A significant difference in frictional levels also existed between the two self-ligating bracket systems (Smart-Clip Metal SL brackets and Damon Clear SL brackets) as shown in the results (Figure 10; Addendum C4). This is in agreement with the literature which reported that metal self-ligating brackets produce lower frictional forces compared with ceramic and polycarbonate self-ligating brackets (Cacciafesta *et al*, 2003; Franchi *et al*, 2008). The research performed by Cacciafesta *et al* (2003) tested conventional stainless steel (Victory Series), stainless steel self-ligating (Damon SL II), and polycarbonate self-ligating brackets (Oyster). Three types of orthodontic wire alloys were tested: stainless steel, nickel-titanium and beta-titanium. All the brackets had a .022” slot and were tested with each type of wire alloy in 3 different sections: 0.016”, 0.017 x 0.025” and 0.019 x 0.025” archwires. The results showed that the stainless steel Damon SL II brackets produced significantly lower static and kinetic frictional resistances than both conventional stainless steel and aesthetic self-ligating brackets.

According to Shivapuja and Berger (1994), the difference in friction levels between stainless steel and polycarbonate self-ligating brackets could be explained by the variance in the structural design of each bracket body, in addition to the material composition of the bracket slot and cap. Another possible explanation is that ceramics have a higher coefficient of friction than stainless steel because of increased roughness and porosity of the material surface (Angolkar *et al*, 1990).

It must be noted that Damon Clear SL brackets produced the lowest mean frictional force when coupled with the round 0.016" Ni-Ti archwires (Figure 12; Addendum E2). However, there was no statistically significant difference when it was compared with the Smart-Clip Metal Self-Ligating brackets coupled with the round 0.016" Ni-Ti archwire. On the other hand, when the Damon Clear SL brackets were tested with 0.019 x 0.025" SS it generated the highest frictional force.

6.2. Comparison between the archwires

Orthodontic archwires are attached to the brackets and aid in moving the teeth to their ideal position in the dental arch. Archwires are available in different cross-sections (round and rectangular), sizes and material compositions. As the treatment progresses the orthodontic archwires are continuously changed. The archwire sequence selected could be case dependent, based on individual preference or dependant on the method of the technique involved.

The One Way Anova test (Figure 11; Addendum D1) indicated significant differences ($P < 0.05$) between the 0.016” Ni-Ti, 0.019 x 0.025” Ni-Ti and the 0.019 x 0.025” SS archwires. The results from this study indicated that less frictional force was obtained with the round Ni-Ti archwire compared with the rectangular Ni-Ti archwires (Figure 11; Addendum D4). This is in agreement with other studies which indicated that the friction increased as the archwire diameter increased (Thomas *et al*, 1998; Cacciafesta *et al*, 2003; Tecco *et al*, 2005). These results correspond with a number of previous studies that stated that the amount of friction increases as the wire breadth increases and that friction is usually more with rectangular wires than with round wires because there is a larger contact area between slot and wire surfaces (Angolkar *et al*, 1990; Pizzoni *et al*, 1998) From the results of the present study it can be concluded that the thickness (size) of the archwire plays an important role in the amount of friction generated.

The rectangular stainless steel archwires generated higher frictional forces than the rectangular Ni-Ti for all the bracket archwire combinations (Figure 11; Addendum D4). These findings are in agreement with studies reported by Angolkar *et al* (1990) and Tselepis *et al* (1994).

However, many other investigations which evaluated the frictional resistance generated by SS and nickel-titanium alloys found conflicting results.

Numerous studies found no significant differences between the 2 types of alloys (Omana et al 1992; Cacciafesta et al, 2003). In the study performed by Omana et al (1992) a single maxillary right cuspid bracket with a 0.022” slot was selected. The friction was tested when 0.018 x 0.025” nickel-titanium and stainless steel archwires were coupled with various ceramic and metal brackets. The study concluded that no appreciable difference existed between the frictional force values of the stainless steel and nickel-titanium archwires. Loftus et al (1999) found similar results using a single premolar bracket. In their study conventional and self-ligating stainless steel brackets as well as conventional ceramic brackets, and ceramic brackets with a stainless steel slot, all with 0.022” bracket slot, were tested with 0.019 x 0.025” archwires of stainless steel, nickel-titanium, and beta titanium. The model used was representative of the clinical condition and allowed for tipping as well as rotations to occur. It was concluded that the highest frictional forces were associated with the beta titanium archwires and that friction with nickel-titanium wires was similar to that of stainless steel.

In contrast to the above mentioned studies, other investigations found higher frictional forces with the nickel-titanium archwires compared with the stainless steel archwires (Nishio *et al*, 2004; Monteiro *et al*, 2014). Nishio *et al* (2004) compared the frictional force generated by ceramic brackets, ceramic brackets with metal reinforced slot, and stainless steel brackets in combination with stainless steel, nickel-titanium, and beta-titanium orthodontic archwires. Brackets and archwires were tested with tip angulations of 0° and 10°. Archwires with a 0.019 x 0.025” dimension of each type were tested: stainless steel, nickel-titanium and beta-titanium.

The result showed that the stainless steel archwires produced the least frictional force value, followed by the nickel-titanium and the beta-titanium wire showing the highest statistically significant frictional force. They found that the frictional force values were directly proportional to the angulation increase between the bracket and the wire.

In the study performed by Monteiro *et al* (2014), the influence of archwire material (Ni-Ti, beta-titanium and stainless steel) and brackets design (self-ligating and conventional) on the frictional force resistance was compared. Self-ligating brackets (Smart-Clip) and conventional brackets (Gemini) with three (0, 5, and 10 degrees) slot angulation were tested. All brackets were tested with archwire 0.019 x 0.025" nickel-titanium, beta-titanium, and stainless steel. The scanning electron microscopy evaluating surface roughness and mechanical tests evaluating friction showed that roughness and friction increased in the same order: stainless steel, nickel-titanium and beta-titanium. With regard to conventional brackets, the stainless steel wires had the lowest friction force values, followed by nickel-titanium and beta-titanium ones. However, the self-ligating brackets (Smart-Clip) exhibited lower friction force when combined with nickel-titanium, stainless steel, and beta-titanium wires, in that order. A possible explanation is the fact that Smart-Clip has nickel-titanium clips, which in contact with wires of the same material could produce lower frictional values (Monteiro *et al*, 2014).

The inconsistencies found between the numerous studies may probably be associated with differences in experimental settings, different number of brackets, or different angulation between bracket and wire, which in many studies was not zero (Ogata *et al*, 1996). Therefore, a direct comparison of the various published studies on this topic is complex. However, the results from this study indicates that the archwire material has a significant influence on the friction generated.

6.3. Brackets and Archwires Combined

Since the orthodontic force must overcome the frictional resistance, minimizing friction will result in reduced levels of force needed for moving the teeth. Such reduction might shorten the treatment period and improve anchorage control (Readlich *et al*, 2003). Low friction may also be favoured during the initial phase of alignment, however, in the last phases, higher friction force can be used to obtain a three-dimensional control of the tooth position (Monteiro *et al*, 2014).

The results showed that the lowest mean frictional force was recorded for the Metal Self-ligating bracket (Figure 10; Addendum C4). However, the Damon Clear self-ligating brackets produced the least amount of friction when coupled with the small round archwire, which is important during the initial levelling and aligning stages of orthodontic treatment. Findings from this study are consistent with previous investigations that metal self-ligating brackets produce lower friction compared with conventional brackets when coupled with small round archwires (Shivapuja and Berger, 1994; Cacciafesta et al, 2003; Tecco et al, 2005; Henao and Kusy, 2005).

Both conventional and self-ligating brackets displayed an increase in the frictional force values as the archwire size increased. When coupled with the larger, rectangular Ni-Ti archwires the frictional resistance increased significantly for all bracket types with the Smart-Clip Metal Self ligating bracket outperforming both the Conventional Victory Series and the Damon Clear Self-ligating brackets (Figure 12). This is in agreement with Monteiro *et al* (2014) who concluded that even at different angulations, the Smart-Clip self-ligating brackets coupled with the 0.019 x 0.025” nickel-titanium wires showed significantly lower frictional force values than the conventional brackets. A reason why rectangular wires produced an increased friction even in self-ligating brackets is that, as the bracket slot is filled, less tipping is allowed before the teeth are straightened back by the wire resilience (Ehsani *et al*, 2009). No significant differences were found between the Conventional Victory Series and the Damon Clear self-ligating bracket when coupled with the 0.019 x 0.025” Ni-Ti archwires. This outcome emphasized the importance of alignment and levelling before using larger wires and sliding mechanics.

Chapter 7

Limitations

The shortfalls of the study include:

1) As with any *in vitro* study, this investigation couldn't accurately mimic what actually occurs in clinical situations because of numerous variables such as chewing forces (Griffiths *et al*, 2005) different types of malocclusion, (Henao and Kusy, 2005), temperature and moisture (Tecco *et al*, 2007) as well as an immense variability in the biological parameters of patients, complicate the matter even further (Rossouw, 2003).

2) The typodont onto which the brackets were fixed did not allow for the initial tipping of the teeth to occur. It has been formerly stated that as the bracket to archwire angulation increases, so does the frictional resistance of a particular bracket and archwire combination (Dickson *et al*, 1994).

3) The study utilized a typodont in which the teeth were in ideal occlusion. According to Rinchuse and Miles (2007) research using models with straight aligned brackets may neglect the influence of the binding effect.

4) In the oral cavity, brackets and archwires are continuously covered with saliva. Our study simulate conditions of the oral environment. However, the result of saliva and its role as a lubricant for decreasing the amount of friction is debatable. Andreasen and Quevedo (1970) found no difference with or without human saliva on frictional resistance. They stated that the role of saliva was insignificant. Kusy et a1 (1991) tested the use of human saliva in their experiments on frictional resistance. They reported that saliva only decreased friction with (beta-titanium and nickel-titanium (Ni-Ti) archwires. The levels registered for stainless steel and chrome-cobalt wires were higher than those obtained in dry state.

Chapter 8

Conclusion

The following conclusion can be drawn from this study:

1) Metal Self-Ligating brackets generated significantly lower frictional forces than both the Conventional Stainless steel and the Damon Clear Self-Ligating brackets. However when coupled with round Ni-Ti archwires the Damon Clear Self-Ligating brackets produced the least amount of friction. Both self-ligating brackets maintain lower friction than the conventional bracket when coupled with small round archwires in the absence of tipping and/or torque in an ideally aligned arch. This is important during the initial, levelling stages of orthodontic treatment in which the least amount of friction is required. Therefore, levelling and alignment of malposed teeth, which begins as part of the initial stage of orthodontic treatment, should be accomplished with flexible archwires.

2) When coupled with the larger, rectangular archwires the frictional resistance increased significantly for all bracket types. A rectangular archwire is often used to complete the initial levelling and aligning stage, express rotation control, and start torque control; it is also usually recommended for space closure (after teeth are well levelled and

aligned),retraction (during which teeth may tip or rotate), and finishing (Ehsani *et al*, 2009).

3) The Damon Clear Self-Ligating brackets produced the highest frictional force when coupled with 0.019 x 0.025" SS archwires. Greater frictional forces mean that an increased number of tipping and uprighting must take place. Thus, friction should be minimized to achieve a more efficient sliding movement of the tooth along the archwire.

Chapter 9

Appendices

9.1. ADDENDUM A

Recommended bracket-positioning chart according to the MBT appliance bracket placement guide (McLaughlin *et al*, 2001).

17	16	15	14	13	12	11	Upper right first quadrant
2	4	5	5.5	6	5.5	6	Unit 1
2	3.5	4.5	5	5.5	5	5.5	Unit 2
2	3	4	4.5	5	4.5	5	Unit 3
2	2.5	3.5	4	4.5	4	4.5	Unit 4
2	2	3	3.5	4	3.5	4	Unit 5

The first row indicates the tooth numbers of the upper first quadrant of the typodont. The following rows (units) are the measurement made from the incisal edge to the middle of the tooth. The height and width of the central incisor of the acrylic typodont was measured and calculated to be 10mm. The measurement was divided in half and the bracket was bonded in the centre of the tooth (5mm from the incisal edge). Unit 3 (highlighted in blue) was then used to bond the remaining brackets at the correct heights onto the typodonts.

9.2. ADDENDUM B

Ethics Approved Registration Letter

UNIVERSITY of the WESTERN CAPE

DEPARTMENT OF RESEARCH DEVELOPMENT

31 May 2017

To Whom It May Concern

I hereby certify that the Senate Research Committee of the University of the Western Cape, at their meeting held on 19 October 2012, approved the methodology and registered the following research project by: Dr J Cupido (Dentistry)

Research Project:	Evaluation of the friction generated by self-ligating and conventional bracket systems in various bracket archwire combinations: an in vitro study.
Registration no:	12/9/10

Any amendments, extension or other modifications to the protocol must be submitted to the Ethics Committee for approval.

The Committee must be informed of any serious adverse event and/or termination of the study.

Ms Patricia Josias
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9.3. ADDENDUM C

Brackets

C1: One- way Anova showed the overall significance. A significant difference existed between the 3 types of brackets (P <0.05)

	Univariate Tests of Significance for Friction Sigma-restricted parameterization Effective hypothesis decomposition				
Effect	SS	Degr. of	MS	F	p
Intercept	25831.35	1	25831.35	3498.585	0.00
Bracket	2884.29	2	1442.14	195.323	0.00
wire	13543.71	2	6771.86	917.177	0.00
Bracket*wire	5686.73	4	1421.68	192.552	0.00
Error	553.75	75	7.38		

All numbers indicated in Red has P<0.05 which means that a significant difference existed.

C2: Tukey HSD test; variable Friction. Approximate Probabilities for Post Hoc Tests Error: Between MS = 7.3834, df = 75.000

Cell No.	Bracket	Smartclip	Victory Series	Damon Clear
1	Smartclip		0,000115	0,000110
2	Victory Series	0,000115		0,000110
3	Damon Clear	0,000110	0,000110	

C3: Tukey HSD test; variable Friction. Homogenous Groups, alpha = .05000 Error: Between MS = 7.3834, df = 75.000

Cell No.	Bracket	Friction	1	2	3
1	Smartclip	11,59667	****		
2	Victory Series	15,22483		****	
3	Damon Clear	22,53280			****

C4: Bracket; Unweighted Means. Current effect: F (2, 75) =195.32, p=0.0000 Effective hypothesis decomposition

Cell No.						
	Bracket	Friction	Friction	Friction	Friction	N
		Mean	Std.Err.	-95,00%	95,00%	
1	Smartclip	11,59667	0,496097	10,60839	12,58494	30
2	Victory Series	15,49511	0,505201	14,4887	16,50152	29
3	Damon Clear	25,91563	0,549346	24,82128	27,00998	25

9.4. ADDENDUM D

Archwires

D1: One- way Anova showed the overall significance. A significant difference existed between the 3 types of archwires (P <0.05)

	Univariate Tests of Significance for Friction Sigma-restricted parameterization Effective hypothesis decomposition				
Effect	SS	Degr. of	MS	F	p
Intercept	25831.35	1	25831.35	3498.585	0.00
Bracket	2884.29	2	1442.14	195.323	0.00
wire	13543.71	2	6771.86	917.177	0.00
Bracket*wire	5686.73	4	1421.68	192.552	0.00
Error	553.75	75	7.38		

D2: Tukey HSD test; variable Friction. Approximate Probabilities for Post Hoc Tests Error: Between MS = 7.3834, df = 75.000

Cell No.	wire	0.016Niti	0.019X0.025 NiTi	0.019x0.025 SS
1	0.016Niti		0,000110	0,000110
2	0.019X0.025 NiTi	0,000110		0,000110
3	0.019x0.025 SS	0,000110	0,000110	

D3: Tukey HSD test; variable Friction. Homogenous Groups, alpha = .05000 Error: Between MS = 7.3834, df = 75.000. This figure indicates that there is a significant difference between the different archwires.

Cell No.	Wire	Friction	1	2	3
1	0.016Niti	3,23567	****		
2	0.019X0.025 NiTi	15,15607		****	
3	0.019x0.025 SS	31,97308			****

D4: Archwire; Unweighted Means. Current effect: F (2, 75) =917.18, p=0.0000 Effective hypothesis decomposition

Cell No.	wire	Friction	Friction	Friction	Friction	N
		Mean	Std.Err.	-95,00%	95,00%	
1	0.016Niti	3,23567	0,496097	2,24739	4,22394	30
2	0.019X0.025 NiTi	15,27825	0,516354	14,24962	16,30688	28
3	0.019x0.025 SS	34,49349	0,538875	33,42	35,56699	26

9.5. ADDENDUM E

Brackets and Archwires combined

E1: Tukey HSD test; variable Friction.

Cell No.	Bracket va wire		Smartclip 0.016Niti	Smartclip 0.019X0.025 NiTi	Smartclip 0.019x0.025 SS	Victory Series 0.016Niti	Victory Series 0.019X0.025 NiTi	Victory Series 0.019x0.025 SS	Damon Clear 0.016Niti	Damon Clear 0.019X0.025 NiTi	Damon Clear 0.019x0.025 SS
1	Smartclip	0.016Niti		0.000134	0.000134	0.026167	0.000134	0.000134	0.888773	0.000134	0.000134
2	Smartclip	0.019X0.025 NiTi	0.000134		0.000134	0.000505	0.019640	0.000134	0.000134	0.013430	0.000134
3	Smartclip	0.019x0.025 SS	0.000134	0.000134		0.000134	0.105301	0.205237	0.000134	0.296109	0.000134
4	Victory Series	0.016Niti	0.026167	0.000505	0.000134		0.000134	0.000134	0.000335	0.000134	0.000134
5	Victory Series	0.019X0.025 NiTi	0.000134	0.019640	0.105301	0.000134		0.000152	0.000134	0.999996	0.000134
6	Victory Series	0.019x0.025 SS	0.000134	0.000134	0.205237	0.000134	0.000152		0.000134	0.000367	0.000134
7	Damon Clear	0.016Niti	0.888773	0.000134	0.000134	0.000335	0.000134	0.000134		0.000134	0.000134
8	Damon Clear	0.019X0.025 NiTi	0.000134	0.013430	0.296109	0.000134	0.999996	0.000367	0.000134		0.000134
9	Damon Clear	0.019x0.025 SS	0.000134	0.000134	0.000134	0.000134	0.000134	0.000134	0.000134	0.000134	

The black numbers indicates that no significance difference exists between the groups

E2: Tukey HSD Test; variable Friction. Homogenous Groups

Cell No.	Bracket	wire	Friction Mean	1	2	3	4	5	6
7	Damon Clear	0.016Niti	0.70100		****				
1	Smartclip	0.016Niti	2.42000		****				
4	Victory Series	0.016Niti	6.58600				****		
2	Smartclip	0.019X0.025 NiTi	12.28000					****	
5	Victory Series	0.019X0.025 NiTi	16.56600	****					
8	Damon Clear	0.019X0.025 NiTi	16.98875	****					
3	Smartclip	0.019x0.025 SS	20.09000	****		****			
6	Victory Series	0.019x0.025 SS	23.33333			****			
9	Damon Clear	0.019x0.025 SS	60.05714						****

Chapter 10

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