University of Alberta

The effects of stainless steel ligature ties on the mechanical characteristics of conventional and self-ligated brackets subjected to torque

by

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Dedication

I would like to dedicate this work to my beautiful wife Dania and my lovely boys Abraham, Noah and Adam. Letters and words no matter how I put them cannot thank you enough for your love and support. Dania, love to me was an abstract term until you showed me how much someone can care for another. In many incidents you made me humble by your patience and forgiveness. My lovely boys, the sound of your laughs and the picture of your innocent faces have never left my mind, and have been the source of energy that kept me going through all the time. To my parents, I am a better man because of you, your sacrifices will always be remembered.

Abstract

Stainless steel ligatures ties are routinely used by orthodontists to improve torque; nevertheless, there is a lack of evidence as to the role of stainless steel ligation in bracket retentive characteristics. The objective of this study is to look into the effects of stainless steel (SS) ligation has on torque and bracket deformation for conventional and self-ligated brackets. A previously described torquing apparatus, combined with an overhead camera, utilized to rotate a .019x.025-inch stainless steel wire in a bracket slot to measure torque (Nmm) and acquire an overhead image at 3° increments of wire rotation from 0° up to 45°, and back again to 0°. A digital image correlation means and two profile images comparisons (before and after) were used to assess the structural changes of the bracket throughout the wire rotation and after the experiment, respectively Sixty Orthos®Twin brackets (Ormco Corp., Glendora, CA, USA), 30 ligated with conventional elastic ties and 30 ligated with SS ligature ties, and sicty Damon Q® brackets (Ormco Corp., Glendora, CA, USA), 30 ligated with its conventional sliding door and 30 ligated with SS ties in addition to the sliding door, were used. The torque was significantly higher for the steel ligated groups over conventional ones from 3°-9° of wire rotation. Overall, steel ligation did increase torque for Orthos twin brackets but it did not for Damon Q brackets. Stainless steel ligature reduces the amount of plastic deformation of both Orthos twin and Damon Q brackets, and a slight decrease in the slot width can be evident when stainless steel ligature is first applied to a bracket. SS ligature ties can be an effective auxiliary tool that could help practitioners to achieve better torque and to reduce bracket deformation.

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List of Abbreviations

ANOVA ....Analysis of variance

CCD ....Charged coupled device

DC ....Damon Q bracket with conventional sliding door

DS ....Damon Q bracket with steel ligation

MANOVA ....Multivariate analysis of variance

MIM ....Metal injection moulding

OMSS...............................Orthodontic measurement and simulation system

SD .... Standard deviation

SS..................................... Stainless steel

TC ....Orthos twin bracket with conventional elastic ligation

TS ....Orthos twin bracket with steel ligation

in ....Inch

mm ....Millimeter

N ....Newton

Nmm ....Newton millimeters

Definitions

Force (N): It is the “general mechanism for changing the mechanical state of an object” and it is “a vector quantity, so it has a direction and a magnitude”.
From: Eberly DH. Game physics. Interactive 3D technology series. 2nd ed. Burlington, MA: Morgan Kaufmann/Elsevier; 2010. p. xlii, 900 p., [16] p. of plates.

Moment of force (Nmm): It occurs when a force is applied to an object, and it causes a tendency for the object to rotate around its axis.
From: Mansfield M, O'Sullivan C. Understanding physics. 2nd ed. Chichester: Wiley; 2011.

Couple (Nmm): “Two forces of equal magnitude, opposite direction, but different lines of action”.
From: Eberly DH. Game physics. Interactive 3D technology series. 2nd ed. Burlington, MA: Morgan Kaufmann/Elsevier; 2010. p. xlii, 900 p., [16] p. of plates.

Torque (Nmm): A moment expressed “by twisting the rectangular orthodontic wire against the walls of the rectangular orthodontic bracket slot”.
From: Major TW, Carey JP, Nobes DS, Heo G, Major PW. Mechanical effects of third-order movement in self-ligated brackets by the measurement of torque expression. Am J Orthod Dentofacial Orthop 2011;139(1):e31-44.

Angle of wire twist or twist angle (degree): The angle at which the wire is twisted within the bracket slot.

Engagement angle (degree): The wire twist angle at which the wire engages into the bracket slot and torque is first expressed.

From: Major TW, Carey JP, Nobes DS, Heo G, Major PW. Mechanical effects of third-order movement in self-ligated brackets by the measurement of torque expression. Am J Orthod Dentofacial Orthop 2011;139(1):e31-44.

Torque play (degree): The range of wire rotation (twisting) in clockwise and counter clockwise directions before the wire engages into the bracket slot and torque is expressed.
From: Major TW, Carey JP, Nobes DS, Heo G, Melenka GW, Major PW. An investigation into the mechanical characteristics of select self-ligated brackets at a series of clinically relevant maximum torquing angles: loading and unloading curves and bracket deformation. Eur J Orthod 2011.

Bracket plastic deformation: A permanent change to "the bracket shape that occurs if the force applied to a bracket exceeds the yield strain of the bracket material". **Bracket elastic deformation:** A non permanent and fully recoverable change to a bracket shape when the load on the bracket is less than the "yield strain" of the bracket material.
From: Melenka GW, Lacoursiere RA, Carey JP, Nobes DS, Heo G, Major PW. Comparison of deformation and torque expression of the orthos and orthos Ti bracket systems. Eur J Orthod 2011.

Introduction

1.1 Introduction

In 1928, Edward Angle, who is considered to be the father of modern orthodontics, invented a technique in which a rectangular archwire is inserted with its side first into a rectangular bracket slot to maintain three dimensional control of a tooth movements "edgewise system"[1]. In the 1970s, Andrews published his articles on ideal occlusion and introduced the idea of "straight wire" technique, in which the straight wire was inserted into a bracket that incorporated required angulations and modifications specific for each tooth[2, 3]. Control of the axial inclination of a tooth in the buccal-lingual direction is accomplished by a force couple introduced by the twisting action of a rectangular wire against the sides of the bracket. The resultant moment acting in the buccal-lingual direction is referred to as torque.

Correct buccal-lingual crown and root angulation is critical to control overbite and overjet[1] as well as proper incisal guidance in protrusive jaw movement. It also influences arch perimeter and the anterior-posterior occlusal relationship in the posterior segments. Buccal-lingual angulation also plays a role in smile esthetics[4]. Buccal-lingual angulation of the canines, premolars and molars influences arch form, occlusal interdigitation and tooth contact in excursive jaw movement[5].

In order to have the "torque expressed" with the straight wire appliance, a rectangular archwire has to be fully seated and secured into the bracket's slot[5].

There are a number of ligation methods that are used to secure the archwire engagement into the bracket. Elastomeric modules are one method used to ligate brackets. However, these elastomers undergo creep and permanently deform to point that there is a near total loss of stiffness within the first 24hrs of use[6], other methods of ligation have been used including fully annealed stainless steel ligatures wires ranging in diameter sizes from .008 to .012 inch[5, 7]. A ligature "locking and tying pliers" is recommended to tie the stainless steel ligatures, in particular when using a heavy archwire to have it snug into the bracket[7].

An intimate relationship between an archwire and a bracket's slot is crucial to provide a needed torque. However, due to size differential between the archwire and bracket's slot walls, torque can be reduced 50% to 100%[8]. Bracket and wire size as well as geometry play a major role in controlling the amount of bracket/wire play (wire rotates in clockwise and counter clock wise with no torque expressed). Nevertheless, ligation method may affect the described play, and stainless steel ligatures was suggested to reduce this play between archwire and bracket's walls[8]. Gioka and Eliades[8] however; provided no explanation on how stainless steel ligatures reduce the bracket-wire play and consequently affects the torque.

In the last few years, there have been number of research papers that discuss bracket deformation as a factor that affects torque of a bracket[9-11]. Researchers[9-11] concluded that depending on the type of bracket and wire design or material used, the deformation varies and the effect on torque is significant. The ligation method was mentioned as a possible factor in determining bracket deformation but again there is no evidence to support that argument[11].

1.2 Problem statement

Stainless steel (SS) ligatures are routinely used by orthodontists to improve the torque expression; however, there are some controversial opinions in the literature on the use of SS ties to better achieve torque expression. Some suggest this is the optimal method[8], while there is no research in the field that describes whether or not SS ties could have an effect on bracket deformation for conventional or self-ligated brackets.

1.3 Objective and methods

In this project, the effects of SS ties on torque will be evaluated and on bracket deformation using conventional and self-ligated brackets. Two types of brackets are used, which can be divided into four groups: 60 Orthos Twin brackets (30 ligated with conventional elastic ties and 30 ligated with SS ligature ties) and 60 Damon Q brackets (30 ligated with its conventional sliding door and 30 ligated with SS ties in addition to the sliding door). A .019x.025-inch stainless steel wire is used in all cases. The experiment procedures and the apparatus that are based on previously published research [4, 9, 12, 13].

1.4 Main hypothesis

There is no difference in the amount of torque expressed as a rectangular archwire goes through first an increasing rotation angles (loading), then a decreasing rotation angles (unloading) between groups ligated with stainless steel ligature ties and groups that are not.

1.5 Secondary hypotheses

1- Torque is first expressed at a smaller angle of wire rotation for the steel ligated groups in comparison to the conventionally ligated groups.

2- Stainless steel ligature ties increase the moment magnitude for each degree of wire rotation.

3- Stainless steel ligature reduces the slot dimensions prior any wire twisting.

4- Stainless steel ligature ties prevent changes in slot dimension (elastic and plastic deformation) while twisting the wire.

1.6 Thesis outline

This thesis document consists of five chapters. The contents of the different chapters are outlined below :

Chapter two, a discussion of the various factors that influence torque, and a review of the available evidence supporting the use of stainless steel ligation to improve torque and limit bracket deformation. Devices used in previous research to measure torque and bracket deformation are also briefly described in this chapter. In Chapter 3the torque experiment is described and discussed. The torque-application apparatus used in the experiment is described along with the associated measurement error. The observed effects of stainless steel ligation on torque of two different bracket systems are described, and factors such as torque magnitude, wire angle at which torque is first expressed (engagement angle) and slot width displacement are reviewed. In Chapter 4 the elastic and plastic deformation for two different bracket systems being tested under stainless steel ligation are evaluated. The impact of stainless steel ligation on these two aspects of bracket deformation is discussed.

Finally, in chapter 5, a discussion and review of the major study findings is presented. Strengths and limitations of the experimental methods, materials, and design are reviewed, and recommendations for future research in this area are provided.

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Chapter 2: Steel ligation effects on torque and bracket deformation literature review

2.1 Introduction

In Orthodontics the term “torque” is used when a force couple is applied to a bracket to stimulate a movement in the root and change the buccal-lingual root inclination. From a clinical point of view, ideal torque will be related to PDL characteristics, root surface area, and certain biological differences[1]. Notwithstanding these differences, in general terms clinically appropriate torque forces have been estimated to be in the range of 0.5 to 2 Ncm for the upper central incisor[2].

In the modern edgewise appliance, torque is planned by cutting the bracket slot at an angle relative to the base, which also referred to as “bracket prescription”. Ideally this would remove the need to do any extra “torquing bend” or twist in the archwire relative to bracket slot, as the straight-wire bracket/wire combination should provide the necessary moment “torque expression” on its own.

The variance in the amount of torque between appliances is greater than the variance of any other feature of modern edgewise appliances[3]. Due to some mechanical and clinical factors, the actual torque expressed is usually different from the manufacturers listed amount.

2.1.1 Mechanical factors:

1- Bracket related Factors:

A- Bracket material: depending on the material of the bracket composition the torque can defer. In general, bracket with a higher modulus of elasticity have the ability of generating higher torque expression[4].

B- Bracket's slot dimension: Meling et al and Odegaard et al[5, 6] have discussed the variation in bracket dimensions caused by the manufacturing process. This variation would affect the range of archwire twist along the long axis of wire in the bracket slot before expressing any moment on the bracket "torque play". The effects reported to be "0.1º of change in torque play corresponds to a 0.9 μm change in slot height"[7].

C- Manufacturer manufacturing tolerances: In some instances and due to manufacturing processing errors, there will be a range of discrepancies between the manufacturer recommendation and the actual torque prescription of a bracket[8].

D- Bracket deformation due to archwire torsion inside the slot may lead to additional "play" between the archwire and the bracket's slot (torque play range is increased) [9].

E- Type of ligation[10].

2- Factors that are related to the archwire used:

A- The archwire material: The difference in stiffness between wires has a significant effect on torsion forces and therefore torque expression: "Steel is four times stiffer than Nitinol in torsion, whereas it is a little less than twice as stiff as TMA"[6].

B- Geometry and shape of the wire: Wire cross-sectional and edge beveling have significant effects on the archwire's properties[5,9-11].

C- Wire deformation: due to the small cross-section of the archwire relative to the bracket, moments applied to the wire are sometimes significant enough to cause plastic deformation to the archwire[12].

2.1.2 Clinical factors:

1. Bracket placement: "Variation of 10°–15° may arise from a vertically inaccurate placement of 1 mm"[4, 13].
2. Crown to root angle variations: there is some variation for the angle between the long axis of the crown relative to the long axis of the root of a tooth. This variation could have significant effects over the correct torque application on that tooth[2, 14].
3. Second order bends: Meling et al[15] have demonstrated that when there is an angle between an archwire and a bracket in the mesial-distal plane of space (second order angle), the torque play in the bracket will be reduced if not eliminated and the torque capability of that bracket will be increased.

4. Inter-bracket distance[2]: the longer the distance between brackets the less force is generated by the wire and the more torsion angle is needed to get the required moments.

Conventional brackets ligated with elastic ties have an inherent problem. As elastics lose their elasticity, the force exerted to keep the wire engaged into the slot is decayed. This is due to number of factors, such as the pH of saliva, temperature, "water sorption" and stretch over time. This loss has been estimated, in vitro, to be about "40% in the first 24 hours" and probably even more in vivo, leading to a "slack in the bracket-wire ligation"[16,7]. Therefore and due to this "slack" a possible loss of wire engagement into the bracket slot may occur which would lead to loss of torque control.

An intimate relationship between the archwire and the bracket slot throughout treatment stages, leading to more predictable outcomes, has increased the attention being focused upon alternative ligation methods, including self-ligation or simply ligating conventional brackets with steel ligatures. Recently, the mode of ligation has become a source of debate in the literature[17], as self-ligated brackets have been advertised as having the potential for less friction, faster treatment and less chair-side time. Notwithstanding these factors, the torque of different ligation methods has not received much attention[4].

The effects of steel ligature ties have been well described in the literature in terms of friction and sliding mechanics, with conclusions that range from no difference observed between ligation methods[18] to: "loosely tied stainless steel ligatures offer the lowest frictional resistance of all the ligation methods tested"[19]. Pandis et al[20] suggests that ligature steel ties should be used in terms of rotational correction "for more efficient and consistent engagement"[20 21]. Moreover, steel ligature holds the archwire tightly into the bracket slot; this effectively reduces the length of the archwire between brackets and therefore increasesthe stiffness of the arch wire[22]. This may have significant effects on the performance of the wire and may increase the torsional forces delivered by the wire.

The role of stainless steel ligature ties on torque has not been fully researched. There is some evidence that steel ligature ties can reduce the slot-wire clearance or slop to provide a better torque expression[7]. This reduction in "clearance" suggests some effects of steel ties on bracket's dimensions.

In this literature review the evidence behind the use of stainless steel ligature ties in terms of torque and bracket deformation will be discussed and critically examined.

2.2 Discussion of the literature

2.2.1 Studies evaluated steel ligation effects on torque

In one recent article, Hirai et al[23] measured torque moments with various archwire, bracket and ligation combinations at target tooth while accounting for the influence of some play between adjacent teeth and the wire. They used ten sets of brackets divided into two groups (five of 0.018x0.025 inch slot, and the other five were 0.022x0.028 inch slot). Each set consists of three stainless steel (SS) twin brackets (central incisor, lateral and canine). Five types of wires were used for each group of brackets: for the 0.018x0.025 inch slot brackets: (0.016x0.022, 0.017x0.022, 0.018x0.025 inch SS wires) and (0.016x22, 0.017x25 inch nickel-titanium (NiTi) wires), and for the 0.022x0.028 inch slot brackets: (0.017x0.025, 0.019x0.025 and 0.021x0.028 inch SS wires) and 0.017x0.025, 0.019x0.025 NiTi wires). The apparatus used had a torque transducer attached to a gauging instrument at one end and to a torquing arm at the other end at which a lateral incisor bracket was attached. Central and canine brackets were bonded on both sides of the lateral incisor bracket to a fixed arm attached to the base of the apparatus. The three brackets were lined up using a "full size" SS wire before they were mounted to the arms. Two types of different ligation methods were evaluated: elastic ties and 0.010 SS ligature ties. For each set of brackets and for each type of ligation method, torque moments were measured five different times using the five wires. Torque moments were measured from 0° to 40° angle at 5° intervals. The authors did not describe their experimental design well enough to be able to understand the sequence in which they used the bracket/wires combination, whether a new wire was used for each test conducted on a bracket with each type of ligation. Any deformation in the brackets or the wires would compromise the findings of their study. Despite the small sample, poor method description and validity of the apparatus used, Hirai et al[23] concluded that torque with SS ligation is "1.1–1.5 times larger than with elastic ligation". However, for full size archwire (.021x.028 inch SS in a 0.022 inch slot) there was no significant difference in torque between the two different ligation methods. There was no further discussion to explain why would SS ligature increase the torque in comparison to elastic ties.

To the contrary, Huang et al[24] used finite elements to compare torque capabilities using various brackets with different ligation methods and archwires. They did not identify a significant difference in terms of torque between conventional brackets ligated with elastic ties and brackets ligated with stainless steel ligature ties. They used 0.022x0.028 inch slot Speed (Strite Industries, Ontario). Damon MX (Ormco, Calif) and conventional Discovery (Dentaurum, Germany)SS brackets. Two types of ligation were used for the Discovery brackets (elastic ties and stainless steel wire ligation). A set of 4 brackets (from the right canine to the left central incisor) for each type of brackets was used in the finite analysis with 0.018x0.025 inch and 0.019x0.025 inch archwires of three different materials (Stainless steel, titanium molybdenum and nickel titanium). Torque was calculated up to 20° at the right central incisors. Nevertheless, the finite element model needs further validation process to correspond to physical certainty[25]. Nonetheless, the authors did note that Discovery brackets had more "maximum moment" than Damon MX brackets (about15Nmm higher) when 0.019x0.025-in SS wire used with 0.022-in slot bracket. Their reasoning was that Discovery brackets had less "play" between the wire and bracket slot. However, there was no further discussion to describe how a wire or an elastic ligation reduces the wire/bracket play. The authors also suggested that active self-ligation (in Speed group) reduced the amount of play between wire and bracket by pushing the wire against the bracket slot. However, but the authors did not explain how a reduction in the amount of play would increase torque of a bracket.

In brackets with active ligation, inserting a rectangular wire at angle into bracket slot would possibly generate two moments. One moment would be generated from the edges of the wire pushing against the bracket slot walls and the other moment from the active door pushing against the corner of the rotated wire at one end and the base of the bracket at the other end. The magnitude of the moment generated by the active ligation would depend on the amount of force of the active door exerted against the wire. The force of ligation can differ from one method to another but it was estimated for conventionally ligated brackets to be the range (0.5 Newton (N) to 3 N)[26]. Khambay et al[26] measured the amount of force generated by stainless steel ligature ties to seat a 0.019x0.025-in SS wire into bracket slot (0.022x0.028 inch) about 3.5N "seating force". The clinical significance of this moment is questionable. Odegaard et al[6] describes this small amount of torque delivered by a ligature as being the result of the "restraining" effects of this ligation without reducing the amount of toque play, but he also acknowledges that the clinical relevance of these torque moments is "doubtful".

Brauchli et al[27] conducted an experiment to assess the effects of active clip designs on torque including brackets ligated with SS ties. They used a sample of five central incisor brackets for each of the nine groups of bracket types: self-ligated brackets (Damon III (Ormco), In-Ovation R (GAC), Oyster (Gestenco International AB), Quick (Forestadent), SmartClip (3M/Unitek), Speed (Strite Industries), Time(American Orthodontics)) and ceramic bracket (Mystique, NeoClip, GAC) and standard twin bracket (Mini-Mono, Forestadent) ligated with elastomeric and SS ligatures. The central incisor bracket was bonded into a frame, which was mounted into a platform supported with six legs (Hexapod) for a precise placement of wire into the bracket, and a rotary table for torque application. A 0.019x0.025 inch SS wire was inserted into the bracket and was fixed into a three-jaw drill clamp that is mounted on a three dimensional torque sensor. Torque were applied from -30° to +30°, and to assess the effects of active clip designs of the bracket ligation method, torque was measured every 100 millisecond in open first then in closed configuration while keeping the same bracket and wire in place. They found no significant difference between the open and closed configuration of all types of brackets, including the twin brackets or the three-ligation configurations (with SS ties, with elastic ties, and no ties). The experiment was conducted first with bracket is open (no ligation) and again in closed fashion. Archambault et al[28] noted in their literature review that when a torque moment is applied to a bracket, notching of the slot of the bracket and "additional widening of the slot by up to 0.016mm" may happen. The deformation of the brackets could be the reason for not finding a significant difference in torque between open and closed bracket configurations in Brauchli's study.

Nevertheless, Brauchli et al[27] reported significant differences in torque between bracket type which they attributed partially to the variation in the actual dimensions of the brackets. They used steel ligated group as a control group and had similar torque to other bracket groups (Damon III and standard twin ligated with elastics) but less than active self-ligated brackets (In-Ovation R) and ceramic brackets (Mystique). They related the higher torque values of the ceramic brackets to the higher "stiffness" in comparison to the other groups. There was no explanation why would "In-Ovation R" group had higher torque than twin brackets ligated with steel ties. Badawi et al[10] also evaluated the mode of active (In-Ovation R) to passive (Damon 2)self-ligated brackets on torque using 0.019x0.025-in SS wire in 0.022-in brackets using a torquing apparatus (brackets mounted onto jigs attached to 3-dimensional multi-axis force transducers which connected to a computer model capable of accurately measuring forces and moments). They also reported a better torque for active self-ligated bracket (In-Ovation R) over passive ones (Damon 2). They related this finding to the active ligation mechanism, which reduced the angle at which torque is first expressed (engagement angle). The engagement angle was 7.5° for the active self-ligating brackets [In-Ovation R] and 15° for the passive self-ligating brackets [Damon 2]". They concluded that active self-ligation does increase the amount of torque when compared to passive self-ligated brackets.

Morina et al[4] have looked at torque between other different brackets, including: self-ligated (Damon2, Speed), and conventional ceramic plastic and Stainless Steel brackets. All brackets were 0.022-inch slot-size and the wire was 0.019x0.025 inch SS. The conventional brackets were ligated with SS ligature ties. They used the "orthodontic measurement and simulation system (OMSS)" apparatus, which uses two 3-D "force–moment" transducers mounted into "motor-driven positioning tables". The apparatus was controlled by a computer and supported with "comprehensive software". Torquing moments were measured on the upper central incisor in a maxillary arch of the "Frasaco model". The study sample was small (five brackets) and there was a lack of detailed explanation as to how they "carefully" level the tooth arch and mount the brackets. Angulations between the archwire and the bracket slot in the mesial-distal plane of space would increase the torque potential of the brackets[15] and therefore adding another variable that would compromise the accuracy of their data. They found that ceramic brackets with SS ligation expressed significantly higher torque over self-ligated brackets and the authors related the difference to the "modulus of elasticity and increased roughness of the slot walls" of the ceramic bracket. They concluded that the mode of ligation does influence the amount of torque expressed with no further discussion or explanation.

It is clear that there is a debate in the literature over the real effects of the ligation method (active, passive, elastics or steel ties) over torque expression. The level of evidence regarding the effects of stainless steel ligature ties on torque is still poor. One important variable that was not accounted for in most of the published research was bracket/wire deformation.

2.2.2 Bracket deformation and steel ligation

Depending on wire and bracket size and geometry, insertion of a rectangular wire at an angle to the bracket slot would result in a moment. This moment creates stress in the bracket, which may lead to elastic (nonpermanent) or plastic (permanent) deformation of the bracket slot walls. The relevance of plastic deformation of a bracket can be described by the increase in the amount of wire rotation in the bracket slot before expressing any moments or increased "torque play angle". Major el al[29] measured bracket deformation using torquing apparatus similar to the one described by Badawi[10], albeit some modifications to measure bracket deformation (adding an overhead camera). Deformation was measured with a high-resolution camera connected to microscope placed over the bracket which. A series of overhead images were taken throughout the torquing experiment. Computer software was used to correlate between the images and record the deformation. They reported a plastic deformation and an increase in the torque play angle "2.1 degrees after 70 Nmm of torque" for 0.022x0.028 inch Speed brackets using 0.019x0.025-in SS wire[29]. Major et al[30], using the same apparatus and 0.022x0.28 inch brackets with 0.019x0.025 inch SS wire, measured plastic deformation and recorded an increase in the width of bracket slot of Damon Q and In-Ovation R in the amount of 0.015mm 0.003mm respectively, after subjecting the brackets to 63° of torque (0° to 63° then back to 0°).

There has been no published research describing bracket deformation (elastic or plastic) with stainless steel wire ligation. In their literature review on torque expression, Gioka and Eliades[7], touched briefly on possible effects of steel ligatures. They described how SS ties tend to "diminish slot-wire clearance, even with large dimensional slot-wire differences". The authors give no discussion as to whether steel ligation produces elastic or plastic dimension change of the bracket to eliminate the described slot-wire clearance. If the steel ligation has enough force to decrease the slot width of a bracket, then it will decrease the amount of torque play and result in more immediate torque of the bracket. Another possible way that SS ligature tie could affect slot dimension is by providing support into the bracket structure and decreasing the amount of bracket deformation (elastically or plastically) and therefore enhancing the performance of the bracket. No evidence yet has been presented in the literature to support the ideas that SS ligature tie could have effects over bracket's dimension or deformation.

2.2.3 Measuring slot dimension:

There are number of methods used to measure slot dimension ranging from a simple use of measuring gauge “leaf gauge”[31] to more complex use of digital cameras connected to microscope then measured through computer software (described before by Major et al[30] and Brauchli et al[27]). Another reported method was to measure bracket dimension using a “scanning electron microscope” and producing images of the slots that were “digitally” measured[32].

2.2.4 Devices used in previous studies to quantify torque expression

Several devices have been used to measure the engagement angle and quantify torque expression. One of the first people to look into torque in 1982 was Hixson et al[33]. They used torque meter Model # 783-C-2 from Power Instruments Inc., Skokie, Illinois after they adapted the device to measure the engagement angle in three different commercial types of standard edgewise 0.022 slot stainless steel brackets. In 1984 Sebanc et al[11] used the same device and demonstrated a greater wire-to-bracket tolerance compared to previous studies. Odegaard et al[6] use a device constructed of 10 mm plastic plates and rods that allow for the wire to be twisted in the center of a plastic crossbar that can rotate around its long axis. Feldner et al[34] in 1994 used a different device using a torque transducer fitted into a bench drill to rotate around the axis of the transducer. In 1994 a study by McKnight et al[35] used an Instron machine (Instron Corp., Canton, Mass) to examine the effects of simulated torque forces on three types of orthodontic brackets. In 1997, Meling et al[12] modified the device previously described by

Odegaard et al[6] to assess the effects of different types and sizes of stainless steel wires. Several researchers (Gmyrek et al[2] in 2002; Harzer et al[36] in 2004, and Morina et al[4] in 2008) used the Orthodontic Measuring and Simulation System (OMSS) device to measure the maximum torquing moment. In 2008 Badawi et al[10] designed the first 3-dimensional multi-axis force transducers connected with a computer software, which is capable of accurately measuring forces and moments applied by orthodontic appliances.

Archambault et al[28] summarized all the previously used torque devices nicely in their literature review. In Table 2.1, we summarize the devices that have been used to date (table 2.1). The newly developed devices that Major et al[25] and Brauchli et al[27] have described used 3D torque transducers. Adding the high resolution camera to the torquing device, Major et al[30] introduced an advantage over any other devices, as it enables them to measure and assess bracket deformation while torque is also assessed.

Table 2.1 description of recent Torque measuring devices.

Author	Measurement device	Objective	Error measurements	Brackets/arch wire used
Brauchli et al[27] (Steel ligated brackets were in the control group, and were not the main subject of investigation).	Bracket mounted to frame attached to Hexapod and 19x25 SS wire fixed to three-dimensional force/moment sensor.	To measure the effects of active clips in self-ligated bracket on torque expression.	10 different measurements for a single MiniMono Bracket 0.022-inch slot.	19x25 SS wire, five of Nine different types of 0.022-in brackets (Damon III, In-Ovation R, Oyster, Quick, Smart Clip, Speed, Time, MiniMono, Mystique) test was done four times up to 30° for each bracket in (open, closed, buccal, and palatal).
Huang et al[24] (Steel ligated brackets were included in the prime objective of the study).	Finite element (FE) Model on four brackets.	To evaluate torque capacity of different Bracket/wire combinations, with respect to (ligation, wire dimensions and properties).	There were no measurements of error.	.022-in slot brackets (Damon MX, Speed, Discovery) wires torqued up to 20° .019x.025-in SS and .018x.025 SS.
Hirai et al[23] (Torque with Steel ligation was one of the primary objective of the study).	Basic design of torque transducer attached to a torquing gauge, three brackets used with middle one used to assess torque.	Measure torque moment with different bracket/wire and ligation combinations.	No error measurement was done.	Five Twin brackets each of .018-inch slot and .022-inch slot brackets. Five archwires for 018 slot brackets: (0.016 × 0.022, 0.017 × 0.025, and 0.018 × 0.025 inch SS wires) and (0.016 × 0.022 and 0.017 × 0.025 inch NiTi). Five more (0.017 × 0.025, 0.019 × 0.025, and 0.0215 × 0.028 inch SS wires) and (0.017 × 0.025 and 0.019 × 0.025 inch Ni-Ti wires) used for the 0.022-inch slot brackets. Every bracket tested five times with two different ligations (steel and elastic).
Major et al[25] (Steel ligation was mentioned in the discussion only).	Multi-axis force transducers, one bracket, an overhead high resolution CCD camera with epi-illuminated microscope.	To assess torque and bracket deformation for number of self-ligated brackets.	The error measurement of the torque transducer is calculated as 1.5%.	.019x25 SS wire, with Damon Q, In-Ovation R and Speed .022-Inch slot brackets.

2.3 Conclusion

Application of torque is an essential part of orthodontic treatment. Torque can vary depending largely on mechanical factors, though some clinical factors also come into play. Stainless steel ligation is used by clinicians for many reasons including better torque of a bracket. A literature review was done to evaluate the evidence regarding use of stainless steel ligatures to have better torque expression. Few papers have published evidence on the use of SS ligatures with no conclusive results. Moreover, no exclusive research is yet available to fully understand the effects of stainless steel on a bracket deformation.

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Chapter Three

Investigation into the effects of stainless steel ligature ties on the mechanical characteristics of conventional and self-ligated brackets subjected to torque

3.1 Introduction

From a mechanical point of view, the definition of torque is used when a body experiences a net moment that causes rotation "about its axis of rotation" due to some external forces[1, 2]. Within orthodontics, a torque is applied to alter the buccal-lingual root angulation of a tooth. This alteration is especially important to provide a proper inter-incisal angle (*i.e.*, the angle between the upper and lower incisors on the sagittal plane) that facilitates the incisal guidance for the anterior (protrusive) movement of the jaw[3]. Anterior buccal-lingual root angulation effects arch perimeter, alignment of anterior teeth, and hence smile esthetics. Furthermore, the buccal-lingual angulations of posterior teeth have considerable effects over occlusal interdigitation and lateral guidance of the jaw movement[4].

When a rectangular wire is twisted or axially rotated within a rectangular bracket slot, torque is generated in the bracket. In the modern edgewise system, the bracket slot is cut at a certain angle (bracket prescription) relative to a straight archwire, so that when a straight rectangular archwire is inserted into the bracket a force couple, *i.e.*, torque, will be generated. The amount of torque is dependent upon the degree of axial rotation of the archwire (referred to as the twist angle, torque angle, or third-order angle) relative to the bracket slot. Depending upon the size of the rectangular archwire, there is a range of possible twist angles that the wire can go through relative to the bracket slot without expressing any torque (termed bracket slop, theoretical play). The angle at which the wire engages the bracket slot and generates a torque is referred to as the engagement angle[5, 6]. The engagement angle may vary and is dependent upon the size of the rectangular archwire and of the bracket slot. For example a 0.019 × 0.025-in wire in a 0.022 × 0.028-in bracket could have between 10.8° to 11.9° of torque play[6]. Morina *et al*[7] previously stressed the importance of this angle in a clinical setting by explaining that the amount of play between the wire and the slot is more important in determining torque than is the design of the bracket.

One of the factors that will affect the engagement angle, and therefore affect the torque expression, is the mode of bracket ligation. Gioka and Eliades[8] discussed the idea that a stainless steel ligature tie would actually diminish the slot-wire play, which would therefore lead to an increased torque value. However, they did not explain how this could happen in practical terms. Two possible effects can be inferred from the Gioka and Eliades[8] study, the first being the possibility of a reduction in slot dimensions if the force of ligation is sufficient to deform the bracket. The second possibility is that by the introduction of a fourth wall in the bracket slot, if the ligation presses the wire against the base of the bracket, rotation of the wire would be resisted by ligation and the base of the bracket, possibly even before the wire could sufficiently rotate to engage the wire edges against the side walls of the bracket.

Understanding the sources of the variations in torque is essential to provide predictable orthodontic treatment results, and the role of stainless steel ligature ties remains controversial. Huang *et al*[9] researched the effects of stainless steel ligation upon torque expression, with their concluding argument being that steel ties will make no difference in terms of torque at 20° for a 0.019 × 0.025-in stainless steel archwire in a 0.022 × 0.028-in bracket.[9] Contrary to the findings of Huang *et al*[9], Hirai *et al*[10] found that by employing a 0.019 × 0.025-in stainless steel wire in a 0.022 × 0.028-in bracket slot, the torque with steel ligation is 1.1–1.5 times larger than with elastic ligation. There was no further discussion made by Hirai *et al*[10] regarding the mechanical role that steel ligation played in increasing the torque expression. While recognizing the limitations of the available research due to the difficulties of controlling many variables (*e.g.*, bracket and wire deformation, and variations in slot dimensions) the real effects of steel ligation remains unclear.

The objective of the present study was to investigate the effects of stainless steel ligature ties on the mechanical characteristics of conventional and self-ligated brackets when those brackets are subjected to a torque.

3.2 Materials and methods

Sample size calculation used the following equation[11]:

$$n = (\sigma_1^2 + \sigma_2^2)\frac{[z_\beta + z_{\alpha/2}]^2}{[\delta]^2}$$

σ_1, σ_2 are the standard of deviations, (δ) is the clinical minimum mean difference to be detected. In this study the significance level considered to be $\alpha = 0.05$, and the power of the study is 90% ($\beta = 0.1$) the z-statistics of α and β are: $z_\beta = 1.28$ and $z_{\alpha/2} = 1.96$ derived from the standard normal distribution.

The clinical minimum difference of torque to be detected is chosen to be as 5Nmm, which is the minimum amount of torque needed to initiate movement in an upper incisor[12].

The standard of deviations are taken from Hirai et al[10] study, they used similar brackets (edgewise Twin brackets) with two different ligations (stainless steel ligature ties and elastic ties). There are number of standard of deviations according related to the torquing angles (5°, 10°,15°, 20°, 25°, 30°). The sample size was calculated at each torquing angle, then an average of those calculations was done to give us an estimation for our sample size, which was 30 brackets for each bracket group.

Two types of upper right central incisor brackets (with slot dimensions of 0.022 × 0.028-in, 15° torque prescription, and 5° tip prescription) were divided into four groups: 60 Ormco Orthos® Twin brackets, comprised of 30 ligated with conventional elastic ties (Ormco Corp., Glendora, CA, USA) (TC group) and 30 ligated with 0.010-in (0.25-mm) tight stainless steel ligature ties (TS group); and 60 Ormco Damon Q® brackets, comprised of 30 ligated with its conventional sliding door (DC group) and 30 ligated with stainless steel ties in addition to the sliding door (DS group). Brackets were torqued with a 0.019 × 0.025-in stainless steel archwire (Ormco Corporation, Orange, CA, USA). New wire was used for every test carried out on each bracket and the principle investigator ran all of the tests on the apparatus. Each bracket was numbered and tested in random order.

3.2.1 Specimen preparation

All brackets were lightly sandblasted using the Ortho Technology TruEtch (50 micron aluminum oxide, item number 12300, The Arum group, Spokane, WA, USA).[13] The sandblasting is performed to alter the surface texture and to create a surface with alternative contrast points in order to provide improved images (through a reduction in the reflectivity of the surface). Bracket slots were physically protected from the sandblasting process by inserting a full-dimensional wire (0.022 × 0.025-in stainless steel) into each bracket during sandblasting. The brackets were then cleaned with water and dried with compressed air. Thereafter, the brackets were glued with epoxy adhesive (Loctite, E-60HP; Hysol, Henkel, Rocky Hill, CT, USA) onto stainless steel cylinders (bracket holders) using a mounting jig to squarely position each bracket at the centre of the bracket holder. A profile image was then taken of the bracket slot using a digital single-lens reflex camera (Canon EOS-D10 10D, Tokyo, Japan) through a microscope (Carl

Zeiss MicroImaging GmbH, Jena, Germany). The bracket holder was then placed into the testing apparatus (see Figure 3.1).

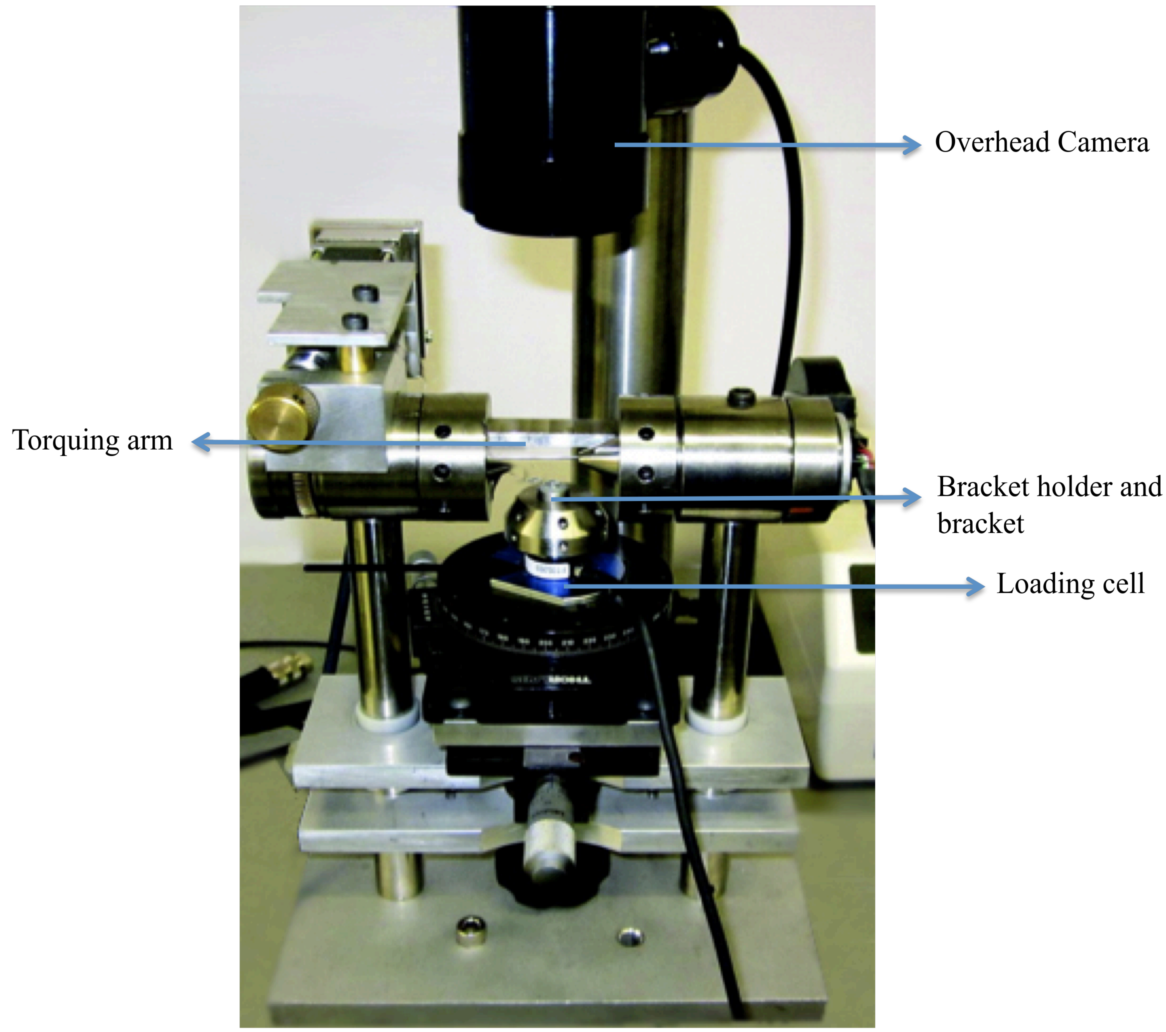


Figure 3.1 Torquing apparatus (adapted from Major et al[5]).

3.2.2 Testing procedures

The test apparatus used in the present study has been described elsewhere (by Badawi *et al.*, 2008 and Major *et al.*, 2011). To summarize, the bracket holder is mounted onto a multi-axis force transducer (loading cell, ATI Industrial Automation Nano 17 Multi-Axis force/torque transducer, Apex, NC, USA). An

Ormco 0.019 × 0.025-in stainless-steel archwire (Ormco Corporation, Division of Sybron, Orange, CA, USA) is inserted and locked into the two beds that are mechanically connected to each other *via* a rigid arm (torquing arm) that is controlled through a stepper motor (Cool Muscle CM1- C-11L30, Myostat Motion Control Inc., Newmarket, ON, Canada). Using a gauging instrument (measuring 5 mm to approximately resemble the inter-bracket distance), the distance between the bracket and the mounting beds of the wire is measured. The bracket holder is tightened and the brackets are ligated.

The imaging apparatus, as described by Lacoursiere *et al*, 2010, has an overhead (over the bracket slot) charged coupled device camera (piA2400-12gm, 2448 × 2050 pixels, 8 bit, gray scale, Basler Vision Technologies, Exton, PA, USA) connected to a microscope (Edmund Optics, 55-908 MMS R4, Barrington, NJ, USA).

Computer software (LabWindows/CVI, National Instruments, Austin, TX, USA) is used to control the stepper motor and to collect data from the loading transducer as well as from the inclinometer (T2-7200-1N inclinometer, USDigital, Vancouver, WA, USA) and the overhead camera. The software also provides real-time feedback *via* an on-screen display of the loads and images of the bracket. This means that it is possible to adjust the bracket position and rotation of the wire so as to ensure that the archwire is fully engaged with the bracket slot with the minimum load at the loading cell (less than 0.3 N and 0.8Nmm in all directions) transmitted between the wire and bracket (previously reported by Major *et al*, 2011). The software was programmed to rotate the wire (clock-wise rotation relative to the bracket slot) from 0° to 45°, then reverse-rotated back to 0°, in order to gather torque measurements and overhead images of the slot every 3° of wire twist angle (from 0° to 45° and back to 0° results in 32 separate measurement points).

Once the overhead images of the bracket slot are collected, a box region in the tie-wings area of the bracket is tracked through the data set. The data image was divided into sub-windows that were linked using a mathematical correlation algorithm[13] to compare the contrast within the image. As a result, a correlation map is recorded that corresponds to the average displacement of the observed image, and therefore the tie-wings. Using a custom code (Matlab, The Mathworks Inc., Natick, MA, USA), the average displacements between the upper and lower tie-wings, or in other words the changes in the slot width (from an overhead perspective) were quantified in millimeter (mm)[13].

The forces (N) and moments (Nmm) that are measured and recorded at the load cell are at different locations from the actual forces and moments generated at the bracket slot (see Figure 3.2). In order to report moments at the bracket slot instead of the loading cell, a method previously described by Major *et al.*, 2011[5] was used to generate the formula:

$$Tx = Tx' - (Fy' * \triangle z) + (Fz' * \triangle y),$$

where Tx and Tx' are the torques at the bracket slot and load cell, respectively; Fz' and Fy' are the forces recorded at the load cell (where the x direction follows the long-axis of the wire, z is vertical to the bracket slot, and y is perpendicular to x and z); and $\triangle z$ and $\triangle y$ are the distances between bracket slot and loading cell in the z and y directions, respectively.

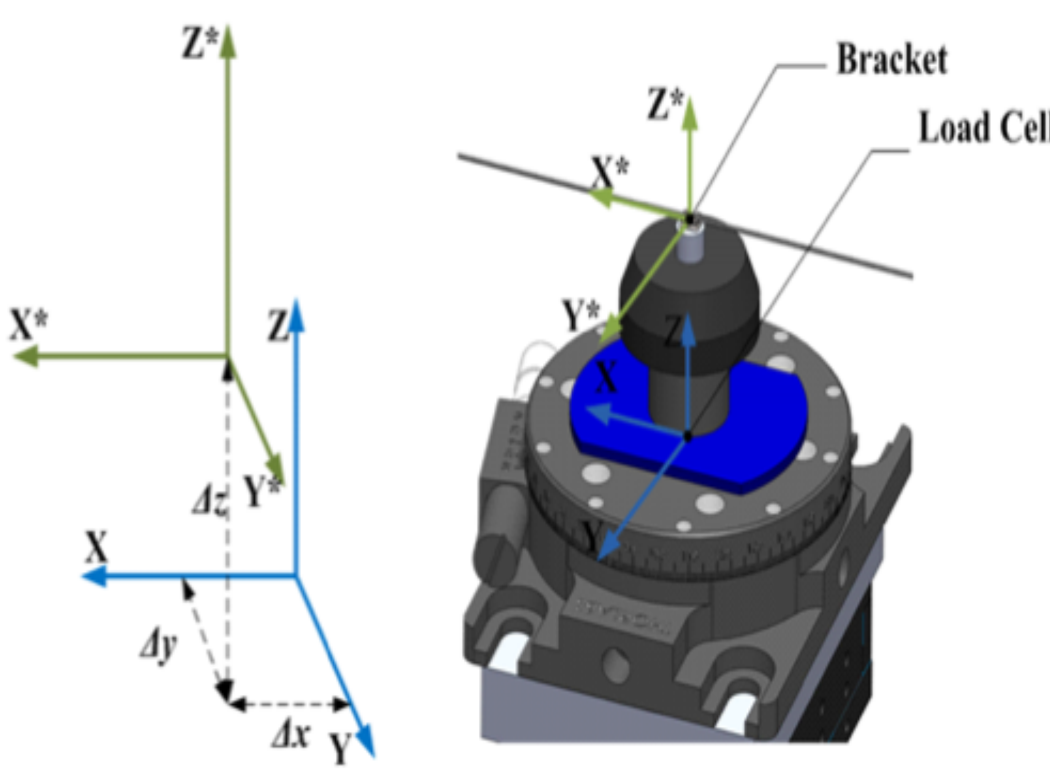


Figure 3.2 Coordinates of the load cell and bracket slot, X* is the direction along the long-axis of the wire, Z* is the direction vertical to the bracket slot, and Y* is the direction perpendicular to X* and Z*. The X, Y, and Z are the directions at the loading cell. △x, △z and △y are the distances between bracket slot and loading cell in the x, z and y directions, respectively[6].

3.2.3 Statistical analysis

For analysis, the statistical package SPSS 19.0 (Chicago, IL, USA) was used to do repeated measures ANOVA and MANOVA. Assumptions of Normality and equality of variance were assessed by boxplots, the Kolmogorov-Smirnov test, and Levene's test. The assumptions were all reasonably met. A *post hoc* multiple comparisons to evaluate the effects of steel ties on the brackets at each angle was done, and because there are three comparisons (TS vs TC, DS vs DC, and TC vs DC) the significance considered using the Bonferroni corrected significance level $0.05/3 = 0.016$ ($p < 0.016$).

3.3 Results

For the 32 torquing angles for all groups, the measured mean of the torque values (Nmm) and their standard deviations are provided in Table 3.1.

The repeated measures ANOVA shows a strong evidence to reject the null hypothesis, which there is no difference in torque magnitude between groups ligated with stainless steel ligature ties and groups that are not, in favor of the alternative hypotheses that there is a difference between bracket types over the range of the angles ($F(3,116) = 16.66$, $p < 0.001$).

Post-hoc multiple comparisons were performed at all angles to observe at which angles any difference between brackets is detected for all groups. Comparison of mean torque expressions between groups, with a 95% confidence interval, is shown in Tables 3.2 to 3.4.

There was no significant ($p > 0.016$) difference found between Damon Q ligated with the conventional sliding door (DC) and Damon Q ligated with stainless steel ties (DS) with the exception of the first 3°-9° as DS had significantly ($p<0.0001$)

higher torque than DC, and the last unloading angle (24° to 0°)as DC had significantly ($p<0.016$) higher torque than DS (Table 3.2).

Table 3.1: Mean torque (Nmm) per angle of twist (°) according to bracket type and ligation method with their standard deviation in parenthesis.

	Torque Angle °	TS Mean (SD)	TC Mean (SD)	DC Mean (SD)	DS Mean (SD)
Loading	0	1.33 (2.40)	0.52 (1.56)	0.01 (1.44)	0.22 (1.36)
	3	6.24 (2.35)	1.16 (1.50)	0.97 (2.02)	4.72 (1.53)
	6	8.91 (3.15)	1.81 (2.18)	2.27 (3.27)	7.17 (2.06)
	9	12.07 (4.31)	3.62 (4.01)	5.73 (3.80)	9.59 (2.70)
	12	17.62 (5.72)	9.19 (5.97)	12.15 (4.48)	13.85 (3.68)
	15	25.89 (7.23)	17.89 (6.91)	20.45 (5.07)	20.86 (4.53)
	18	35.53 (8.23)	27.63 (7.32)	29.89 (5.54)	29.80 (5.14)
	21	45.62 (8.55)	37.49 (7.47)	40.00 (5.70)	39.64 (5.48)
	24	55.51 (8.46)	47.05 (7.52)	50.19 (5.77)	49.71 (5.75)
	27	65.01 (8.20)	56.23 (7.48)	60.28 (5.78)	59.77 (5.93)
	30	74.06 (7.87)	65.01 (7.29)	70.05 (5.87)	69.70 (6.10)
	33	82.29 (7.43)	72.81 (7.11)	79.20 (5.79)	79.10 (6.19)
	36	89.47 (7.00)	79.44 (7.10)	87.55 (5.52)	87.17 (6.22)
	39	95.72 (6.58)	85.44 (6.94)	94.74 (5.32)	94.27 (6.27)
	42	101.05 (6.19)	90.55 (6.77)	100.86 (5.14)	100.20 (6.27)
	45	105.59 (5.88)	94.73 (6.62)	105.85 (4.99)	105.04 (6.19)
Unloading	45	104.28 (5.79)	93.55 (6.55)	104.70 (4.95)	103.82 (6.07)
	42	88.98 (5.57)	78.96 (6.24)	90.30 (4.74)	88.94 (5.79)
	39	74.99 (5.39)	65.60 (5.95)	76.99 (4.52)	75.27 (5.52)
	36	61.90 (5.19)	53.18 (5.70)	64.65 (4.30)	62.56 (5.26)
	33	49.84 (5.07)	41.95 (5.27)	53.17 (4.09)	50.87 (5.02)
	30	38.22 (4.87)	30.66 (5.08)	42.39 (3.83)	39.66 (4.64)
	27	27.69 (4.55)	20.76 (4.76)	32.80 (3.59)	29.50 (4.26)
	24	18.30 (4.14)	12.32 (3.91)	23.93 (3.45)	20.48 (3.89)
	21	10.57 (3.58)	6.57 (2.60)	15.92 (3.24)	12.77 (3.43)
	18	5.06 (3.28)	2.88 (2.05)	9.70 (2.94)	6.68 (2.88)
	15	2.11 (2.71)	0.50 (1.51)	4.06 (2.53)	1.38 (2.20)
	12	1.34 (2.28)	0.09 (1.50)	1.16 (2.22)	-0.41 (1.56)
	9	0.70 (1.96)	-0.02 (1.43)	0.68 (1.99)	-0.68 (1.33)
	6	0.10 (1.63)	-0.21 (1.43)	0.53 (1.78)	-0.78 (1.22)
	3	-0.16 (1.62)	-0.30 (1.45)	0.43 (1.67)	-0.88 (1.19)
	0	-0.96 (1.81)	-0.58 (1.50)	0.43 (1.63)	-1.53 (1.45)

TS: Orthos Twin with stainless steel ligation, TC: Orthos twin with conventional elastic ligation, DC: Damon Q with conventional sliding door, DS: Damon Q with stainless steel ligation in addition to the sliding door.

Table 3.2. Comparison of torque (Nmm) between Damon Q bracket with steel ligation (DS) and Damon Q bracket conventionally ligated (DC) at each collection angle (°).

	Torque Angle°	Mean Difference (DS-DC)	P-Value	95% Confidence Interval	
				Lower Bound	Upper Bound
Loading Angles (ascending)	0	0.21	>0.99	-1.00	1.41
	3	3.76	< 0.0001	2.45	5.06
	6	4.90	<0.0001	3.01	6.78
	9	3.86	<0.0001	1.26	6.46
	12	1.70	>0.99	-1.80	5.20
	15	0.42	>0.99	-3.78	4.61
	18	-0.08	>0.99	-4.71	4.55
	21	-0.36	>0.99	-5.15	4.44
	24	-0.48	>0.99	-5.31	4.35
	27	-0.51	>0.99	-5.31	4.29
	30	-0.35	>0.99	-5.08	4.39
	33	-0.10	>0.99	-4.72	4.52
	36	-0.38	>0.99	-4.88	4.12
	39	-0.47	>0.99	-4.84	3.90
	42	-0.65	>0.99	-4.90	3.59
	45	-0.81	>0.99	-4.93	3.31
Unloading Angles (descending)	45	-0.88	>0.99	-4.95	3.18
	42	-1.36	>0.99	-5.25	2.53
	39	-1.72	>0.99	-5.44	2.00
	36	-2.09	0.708	-5.65	1.47
	33	-2.30	0.428	-5.68	1.09
	30	-2.73	0.146	-5.94	0.48
	27	-3.30	0.022	-6.29	-0.31
	24	-3.45	0.005	-6.12	-0.77
	21	-3.15	0.002	-5.40	-0.91
	18	-3.02	<0.0001	-4.98	-1.06
	15	-2.68	<0.0001	-4.26	-1.10
	12	-1.57	0.012	-2.90	-0.23
	9	-1.36	0.014	-2.55	-0.18
	6	-1.31	0.007	-2.37	-0.25
	3	-1.32	0.005	-2.35	-0.28
	0	-1.96	<0.0001	-3.06	-0.85

Stainless steel ties made a significant difference ($p < 0.016$) for Orthos Twin brackets, consistent with an increase in torque for stainless steel ligation group (TS) over elastic ligation group (TC) at all angles (with the exception of the last 18° of the unloading, see Table 3.3).

In order to form comparisons between the two types of brackets (*i.e.*, Damon Q *vs*. Orthos Twin), a comparison between the mean of DC *vs*. TC was done (Table 3.4). There was no difference ($p>0.016$) between DC and TC upon loading from 0° to 30° twist angle. However, after loading angle of 30° DC had a significantly ($p < 0.016$) higher torque than TC until the unloading angle of 12°.

The torque vs. angle of wire twist figure is presented in (Figures A, Appendix). At each 3° of wire twist a new data point is recorded for the torque measurement up to 45° and back to 0°. The shapes of the curves were similar for the steel ligated groups (DS and TS) and the same for the conventionally ligated brackets (DC and TC). TC group showed consistently less torque per angle of wire twist in comparison to all other bracket groups.

Table 3.3: Comparison of torque (Nmm) between Ormco OrthosTwin bracket with steel ligation (TS) and elastic ligation (TC) at each collection angle (°)					
	Torque Angle (Degrees)	Mean Difference (TS-TC)	P-value	95% Confidence Interval	
				Lower Bound	Upper Bound
Loading Angles (ascending)	0	0.80	0.455	-0.40	2.01
	3	5.08	< 0.0001	3.78	6.39
	6	7.11	< 0.0001	5.22	8.99
	9	8.45	< 0.0001	5.85	11.05
	12	8.44	< 0.0001	4.94	11.94
	15	8.00	< 0.0001	3.81	12.19
	18	7.91	< 0.0001	3.28	12.54
	21	8.14	< 0.0001	3.34	12.93
	24	8.46	< 0.0001	3.63	13.29
	27	8.79	< 0.0001	3.99	13.59
	30	9.05	< 0.0001	4.31	13.78
	33	9.48	< 0.0001	4.87	14.10
	36	10.03	< 0.0001	5.54	14.53
	39	10.28	< 0.0001	5.91	14.66
	42	10.50	< 0.0001	6.26	14.74
	45	10.86	< 0.0001	6.73	14.98
Unloading Angles (descending)	45	10.74	< 0.0001	6.67	14.80
	42	10.02	< 0.0001	6.13	13.91
	39	9.38	< 0.0001	5.66	13.11
	36	8.72	< 0.0001	5.16	12.28
	33	7.89	< 0.0001	4.51	11.28
	30	7.56	< 0.0001	4.35	10.77
	27	6.93	< 0.0001	3.94	9.92
	24	5.98	< 0.0001	3.30	8.65
	21	4.00	< 0.0001	1.76	6.24
	18	2.18	0.021	0.22	4.13
	15	1.61	0.044	0.03	3.19
	12	1.24	0.083	-0.09	2.58
	9	0.72	0.615	-0.46	1.90
	6	0.32	>0.99	-0.74	1.38
	3	0.13	>0.99	-0.90	1.17
	0	-0.37	>0.99	-1.48	0.73

Table 3.4: Comparison of torque (Nmm) between Twin bracket with elastic ties (TC) and Damon Q bracket conventionally ligated (DC) at each collection angle(°).					
	Torque angle (Degree)	Mean Difference (TC-DC)	P-Value	95% Confidence Interval	
				Lower Bound	Upper Bound
Loading Angles (ascending)	0	0.51	>0.99	-0.692	1.719
	3	0.19	>0.99	-1.113	1.496
	6	-0.46	>0.99	-2.351	1.423
	9	-2.11	0.188	-4.715	0.491
	12	-2.96	0.150	-6.462	0.537
	15	-2.56	0.625	-6.748	1.634
	18	-2.26	>0.99	-6.891	2.367
	21	-2.51	0.978	-7.304	2.287
	24	-3.14	0.504	-7.970	1.694
	27	-4.05	0.152	-8.849	0.747
	30	-5.04	0.030	-9.778	-0.309
	33	-6.39	0.002	-11.011	-1.773
	36	-8.11	< 0.0001	-12.608	-3.612
	39	-9.30	< 0.0001	-13.675	-4.933
	42	-10.30	< 0.0001	-14.547	-6.061
	45	-11.12	< 0.0001	-15.241	-6.993
Unloading Angles (descending)	45	-11.16	< 0.0001	-15.225	-7.093
	42	-11.34	< 0.0001	-15.233	-7.452
	39	-11.39	< 0.0001	-15.107	-7.663
	36	-11.47	< 0.0001	-15.027	-7.905
	33	-11.22	< 0.0001	-14.601	-7.831
	30	-11.73	< 0.0001	-14.938	-8.521
	27	-12.04	< 0.0001	-15.028	-9.051
	24	-11.60	< 0.0001	-14.276	-8.929
	21	-9.36	< 0.0001	-11.599	-7.116
	18	-6.82	< 0.0001	-8.776	-4.862
	15	-3.56	< 0.0001	-5.143	-1.979
	12	-1.06	0.206	-2.398	0.270
	9	-0.71	0.667	-1.886	0.475
	6	-0.75	0.368	-1.808	0.314
	3	-0.73	0.376	-1.763	0.311
	0	-1.01	0.095	-2.121	0.098

The levels of displacement of the brackets over all angles are displayed in Table 3.5. Overall, the amount of deformation for brackets that are conventionally tied is consistently higher than when the brackets are tied with stainless steel, and Orthos twin brackets had higher average displacement in compassion to Damon Q brackets.

Table 3.5: Average bracket slot width displacement (mm) per angle of wire twist (°) for all bracket groups with the standard of deviation SD (mm).

Torque angle°	TS		TC		DS		DC	
	Average	SD	Average	SD	Average	SD	Average	SD
0	0	0	0	0.0000	0	0.0000	0	0.0000
3	-0.0004	0.0004	0.0000	0.0001	-0.0005	0.0004	0.0001	0.0005
6	-0.0005	0.0006	0.0002	0.0002	-0.0007	0.0007	0.0004	0.0008
9	-0.0002	0.0012	0.0006	0.0007	-0.0004	0.0011	0.0019	0.0015
12	0.0009	0.0020	0.0022	0.0012	0.0008	0.0015	0.0045	0.0021
15	0.0027	0.0027	0.0046	0.0015	0.0032	0.0018	0.0079	0.0025
18	0.0052	0.0032	0.0074	0.0018	0.0062	0.0020	0.0117	0.0028
21	0.0079	0.0037	0.0106	0.0022	0.0097	0.0021	0.0157	0.0030
24	0.011	0.0041	0.0142	0.0025	0.0132	0.0023	0.0199	0.0031
27	0.0143	0.0046	0.0183	0.0029	0.0168	0.0025	0.0242	0.0033
30	0.018	0.0052	0.0228	0.0034	0.0203	0.0026	0.0286	0.0037
33	0.0219	0.0059	0.028	0.0041	0.0238	0.0027	0.033	0.0039
36	0.0261	0.0067	0.0339	0.0051	0.0272	0.0029	0.0374	0.0041
39	0.0304	0.0076	0.0404	0.0064	0.0304	0.0031	0.0416	0.0043
42	0.0348	0.0086	0.0476	0.0082	0.0332	0.0032	0.0455	0.0046
45	0.0391	0.0097	0.0557	0.0108	0.0358	0.0034	0.049	0.0050
45	0.0394	0.0098	0.0561	0.0109	0.0359	0.0034	0.0491	0.0051
42	0.0391	0.0096	0.0551	0.0109	0.0354	0.0034	0.0481	0.0051
39	0.0384	0.0095	0.054	0.0106	0.0346	0.0033	0.0468	0.0051
36	0.0375	0.0093	0.0524	0.0103	0.0335	0.0032	0.0452	0.0050
33	0.0362	0.0090	0.0503	0.0101	0.0319	0.0031	0.0428	0.0050
30	0.0343	0.0087	0.0475	0.0100	0.0295	0.0030	0.0393	0.0049
27	0.032	0.0085	0.0444	0.0099	0.0262	0.0030	0.0349	0.0046
24	0.0293	0.0082	0.0408	0.0096	0.022	0.0030	0.0297	0.0043
21	0.0263	0.0078	0.0366	0.0093	0.0174	0.0030	0.0238	0.0040
18	0.0225	0.0075	0.0321	0.0093	0.0127	0.0030	0.018	0.0039
15	0.0184	0.0067	0.0279	0.0086	0.0076	0.0026	0.0119	0.0032
12	0.0171	0.0062	0.027	0.0085	0.0054	0.0017	0.0084	0.0025
9	0.0168	0.0062	0.0269	0.0085	0.0052	0.0014	0.0077	0.0021
6	0.0168	0.0063	0.0269	0.0085	0.0052	0.0014	0.0075	0.0022
3	0.0168	0.0063	0.0268	0.0085	0.0052	0.0013	0.0074	0.0021
0	0.0168	0.0063	0.0268	0.0085	0.005	0.0013	0.0073	0.0021

TS: Orthos Twin with stainless steel ligation, TC: Orthos twin with conventional elastic ligation, DC: Damon Q with conventional sliding door, DS: Damon Q with stainless steel ligation in addition to the sliding door.

3.4 Discussion

3.4.1 Torque magnitude

Torque arises from the engagement of the torsion of rectangular wire in a rectangular bracket slot. The overall objective of this study was evaluate if stainless steel ligatures would alter the torque expression, and if so, in what form this change would take for a given bracket type.

Relatively little research has been attempted to measure and describe the torque characteristics with different ligations. This may primarily be due to the difficulties in controlling the large number of variables in a clinical setting compared to those observed in a laboratory[9].

One of the major differences between the present experiment and the clinical setting is the fact that the wire was fixed to mounting dies on both sides of the bracket, with no possibility of any play or other movement[9, 10, 14]. The torque generated in our experiment would most probably be higher than those in clinical cases where the root movement within the periodontal ligament space and the engagement angle of the wire at adjacent brackets will significantly reduce the torque generated at the target bracket. Therefore, clinically to generate greater torque at a certain tooth it is critical to have the archwire anchored firmly to the adjacent brackets.

In the present study the wire is inserted passively into the bracket slot, ligated, and then torqued. The steel tie played a role in restricting the twisting movement of the wire inside the bracket. This restriction can be understood as the ligation acting as the bracket's fourth wall. Although the role of stainless steel ligature as a bracket fourth wall is a 3-D phenomena, the discussion of this role will be in two-dimensional only to simplify this concept. The tight stainless steel ligation presses the wire against the base of the bracket and pushes against the tie wings of the bracket to decrease the slot width (Figure 3.3 A) at this stage no torque should be exerted on the bracket. As the wire rotates inside the slot, it would be resisted by the ligature at one end and the base of the bracket at the other end (termed ligature engagement). This ligature engagement occurs even before the wire can rotate sufficiently to engage the sidewalls of the bracket slot (Figure 3.3 B).

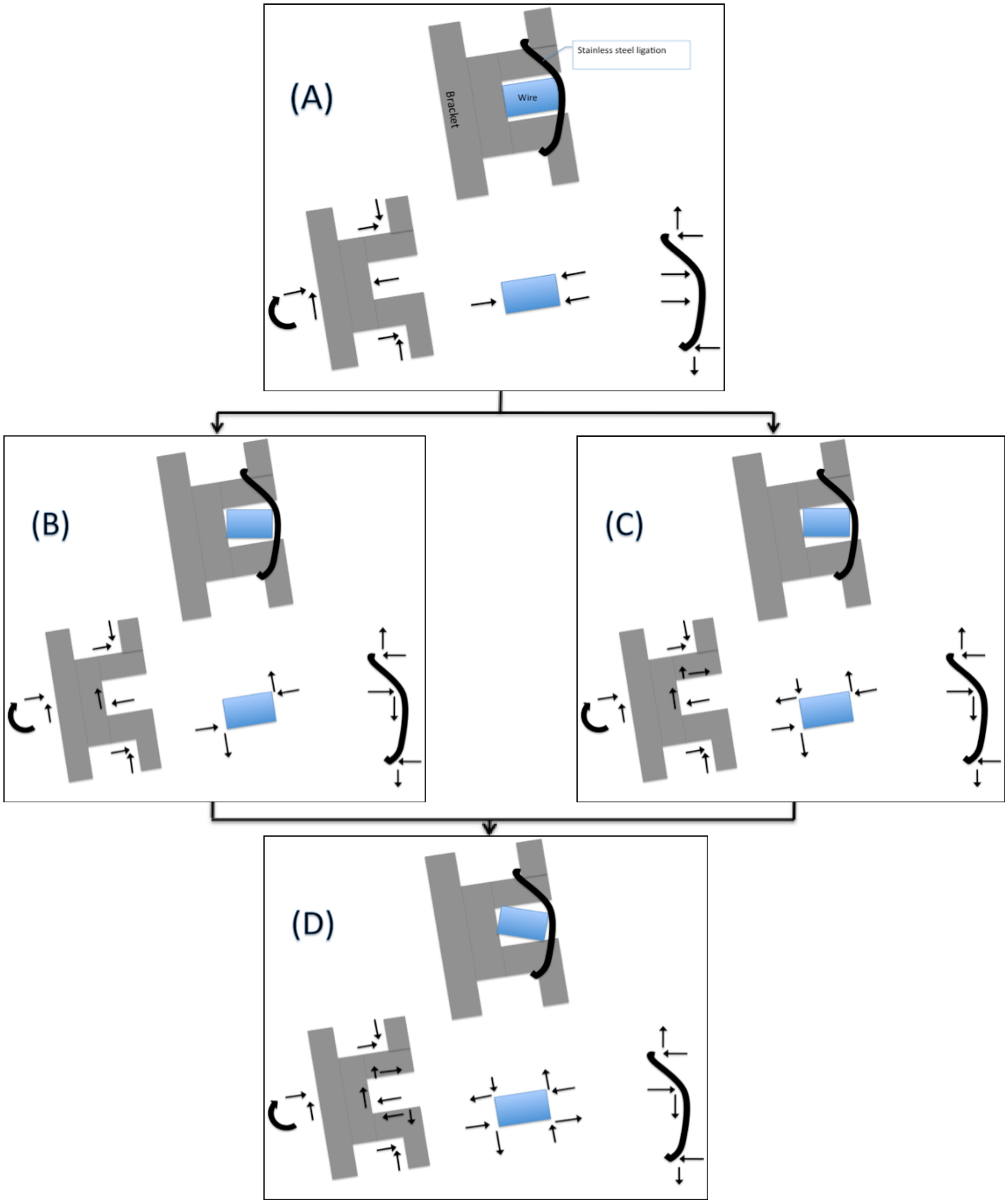


Figure 3.3 Two-dimensional diagrams represent a profile image of a bracket with the archwire and the steel ligation. The arrows represent forces and couples exerted at each part (bracket, wire, and steel ligation) separately as wire rotate (A) wire is at 0° the steel ligation exerting some forces on the wire and bracket, no motion is occurring, (B) wire rotated but not engaged yet with the slot walls, steel ligation forces has resulted in a couple at the wire and the bracket, (C) wire rotated to same degree as in (B) but was engaged with one slot wall only, and (D) wire rotated and now engaged into the slot walls forming a couple that is larger than the couple formed by the ligature.

Torque is generated at the bracket as the wire rotates and is engaged between the stainless steel ligation and the base of the bracket (Figure 3.3 B and C). This relatively small moment can also be identified in (Figure 3.4) as steel ligation groups (DS and TS) expressed significantly ($p < 0.0001$) higher moments for the first 3° to 9° of wire twist than the groups without steel ligation.

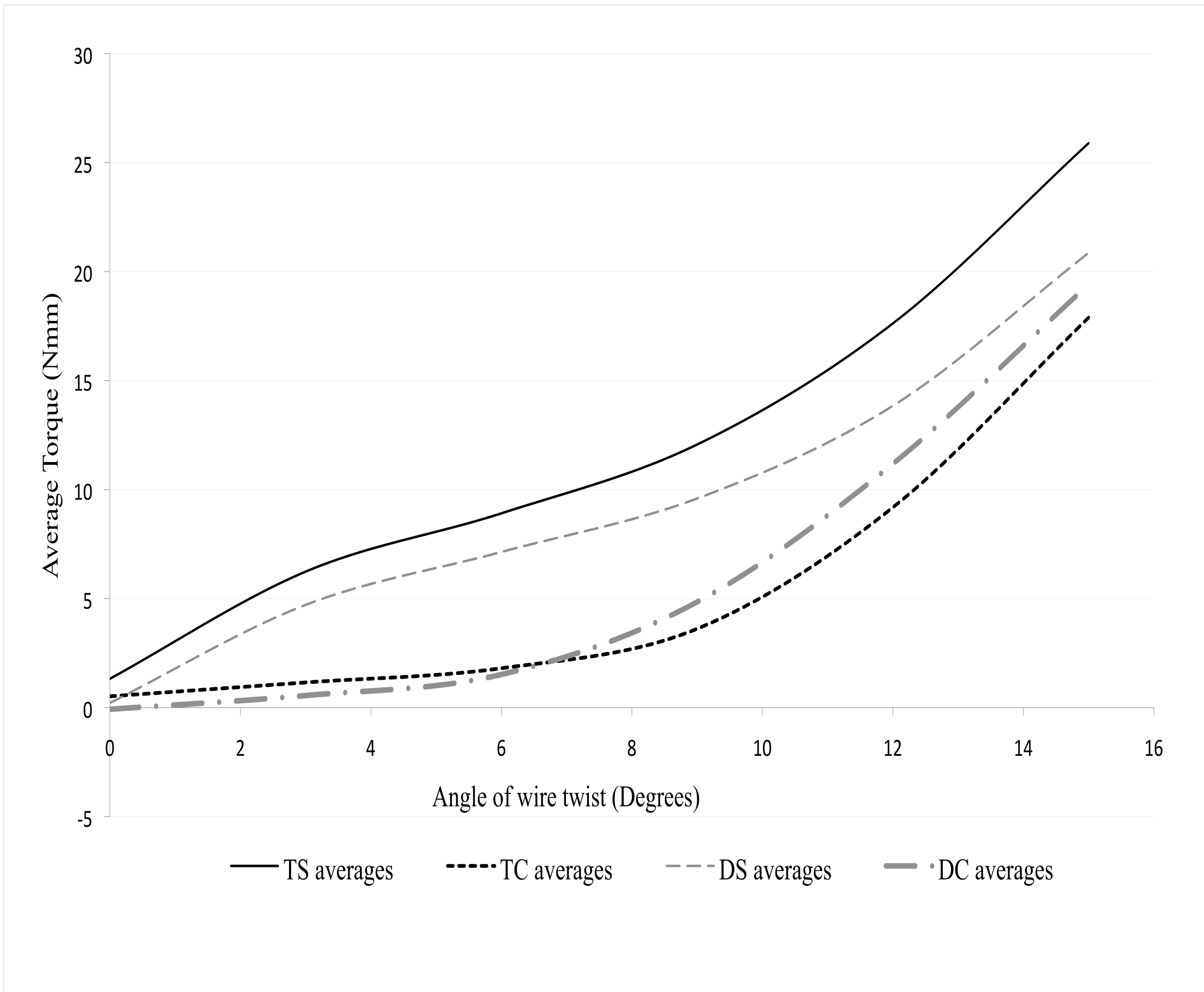


Figure 3.4 First 15° of loading of averaged torque (Nmm) vs. wire twist angle (degrees) for all brackets groups.

The magnitude of the moment generated when a tight steel ligation placed on a bracket with rotated archwire will depend upon the amount of force that the steel ligation delivers to resist the movement of the archwire. Khambay *et al*[15] reported the force generated by stainless steel ligature ties to seat a 0.019 × 0.025-in stainless steel wire into a Twin bracket slot (0.022 × 0.028 in) to be about 3.5N. In our experiment, as the wire rotates and the ligature acts to resist wire rotation, the torque at the bracket will increase (Figure 3.3 B). Therefore, there will be additive effects of couple generated by the wire contacting with the ligature and the couple generated by the wire when contacting the walls of the bracket, and as the wire rotation increases the bracket wall couple will become more dominate since the distance between the forces of this couple is larger than the distance of the couple generated by the ligature (Figure 3.3 D).
Moreover, the range of clinically appropriate torque has been reported as 5-20 Nmm, though there is very little evidence to support this estimate[12, 16, 17]. As identified in Figure 3.4, as the wire is twisted the torque magnitude with steel ligation increases to approximately 5Nmm before the engagement angle of the wire against the walls of the bracket slot are reached. Clinically relevant torque can be reached considerably sooner with steel ligation.

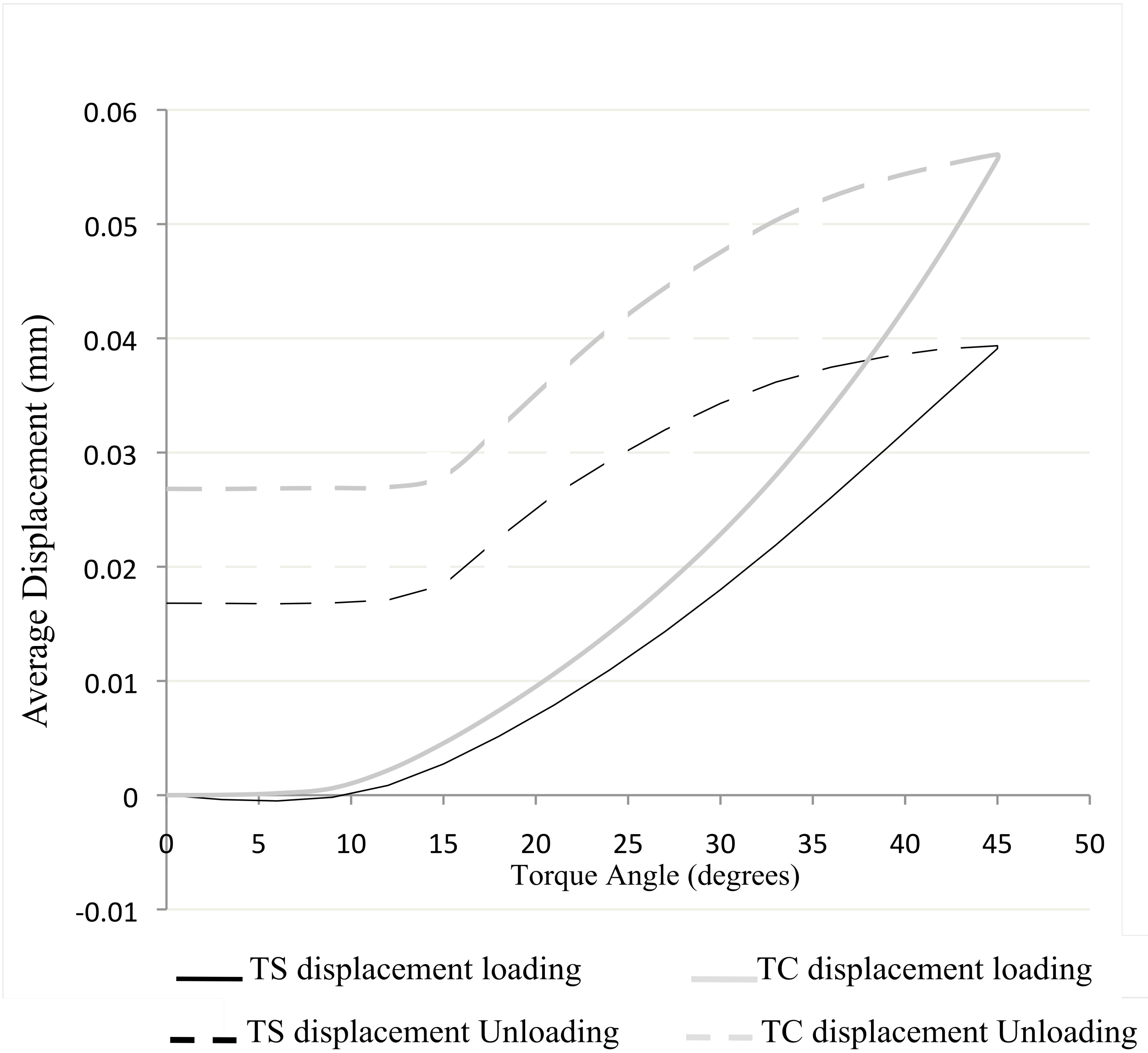
The loading and unloading curves for the experiment groups have similar shapes. Overall, the torque generated during unloading are considerably less than the torque upon loading, most likely as a result of some plastic (permanent) deformation of the wire and/or bracket[6, 18]. From a clinical point of view, the unloading curve is more important, than the loading curve. This is because when a twisted wire is inserted into a bracket the loading action occurs instantly, while the unloading action is sustained during active tooth movement. When the unloading torque drops below the threshold (5 Nmm) to induce tooth movement, no further movement will take place[3].

In this study, the unloading curve (for all brackets) commenced at 45°. Although there is no agreement in published literature regarding the maximum wire twist angle that would be clinically useful, it is unlikely that the twist angle would exceed 45 degrees. In our experiment, the torque generated at the unloading angle of 27° for TC and at 24° for TS, DS, and DC are 18–23 Nmm, and in line with the previously recommended torque magnitude. All four experimental groups dropped below 5Nmm at the 15° unloading angle.

When compared between the groups TC and TS, during unloading from 27° to 0°, it is clear that steel ties only made a difference from 27° to 21° (Table 3.3). For the final 18° (unloading 18° to 0°), no significant difference ($p > 0.016$) was identified, which is probably due to some bracket or wire plastic deformation[19], and most likely a deformation to the stainless steel ligature tie (possibly stretching) enough to diminish the seating force of this ligature and to eliminate the effects of stainless steel ties that were reported upon loading.

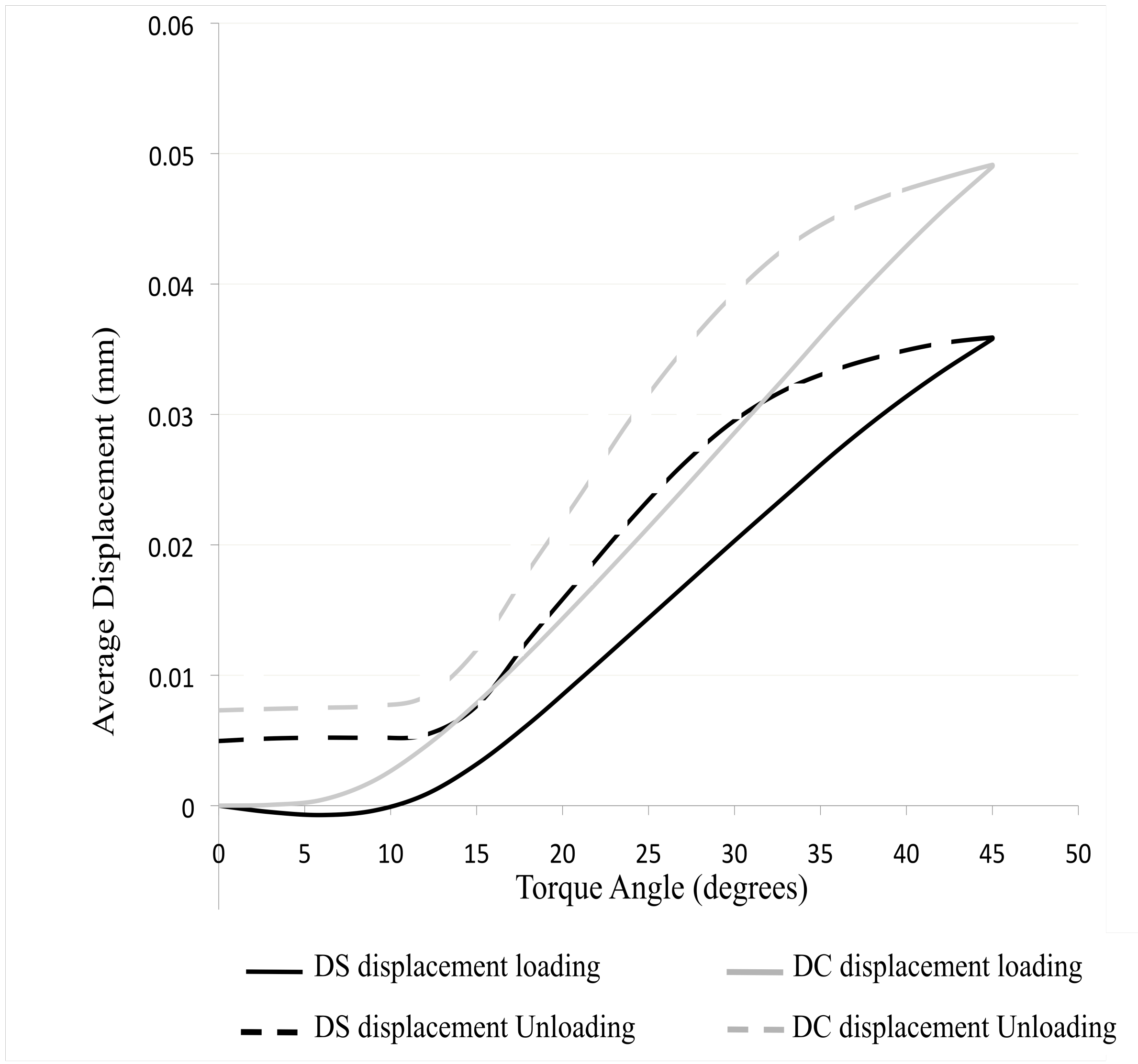
3.4.2 Bracket deformation and torque expression

In order to explain some of the reasons behind the observed differences in torque between Orthos twin steel-ligated brackets (TS) and Orthos twin conventionally ligated brackets (TC), it is necessary to assess the bracket displacement data. Initial stainless steel ligation produced a slight decrease in slot width. As the wire was twisted the stainless steel ligature resisted the increase in slot width (deformation). The increase in bracket slot width starts at around 10° for TS, but starts at around 4° for TC (Figure 3.5A).



A

Figure 3.5A Average displacement (mm) versus angle of wire twist (degrees) for Twin Orthos brackets conventionally ligated with elastic ties (TC) and Twin Orthos brackets ligated with stainless steel ties (TS).



B

Figure 3.5B Relative displacement (mm) versus angle of wire twist (degrees) for Damon Q brackets conventionally ligated (DC) and Damon Q brackets ligated with stainless steel ties (DS).

After 10° of loading there is a continuous increase in the amount of deformation as the angle of twist increases for both types of brackets. The bracket deformation was considerably less for the SS ligature group at maximum wire rotation. Both groups showed recovery in slot width up to 15 degrees. There was permanent (plastic) deformation in both groups, with the amount of deformation being less in the stainless steel ligation group. A similar behavior occurs with Damon brackets with less plastic deformation. (Figures 3.5B). The stainless steel ligature reduced the amount of plastic deformation for Orthos twin brackets by 0.01mm (10 μm) and for Damon Q brackets by 0.00235mm (2.4 μm) (Table 3.5). At 45° wire torsion angle, steel ligation reduced maximum deformation (elastic and plastic) in amount of 0.0132mm (13.2 μm) and 0.016mm (16 μm) for Damon Q and Orthos twin brackets respectively (see Table 3.5). These deformation effects should be considered in relation to the specific bracket/archwire used (in our case, 0.019 × 0.025-in stainless steel wire in a 0.022 × 0.028-in bracket).

In the literature, Brauchli et al[20] did not find a difference between steel ligated and elastic ligated brackets (moments were applied from -30° to +30° with 0.019 × 0.025-in stainless steel archwire and 0.022 × 0.028-in brackets). They measured torque every 100 millisecond in open (no ligation) first then in closed configuration (elastic or steel ligation) while keeping the same bracket and wire in place. A possible explanation for not finding a difference would be the fact that they used the same bracket and wire which could have introduced some deformation to both the bracket and the wire, and this new variable (deformation) can compromise their findings. It is possible that the effects of steel ligation could not make up for the amount of lost torque due to the bracket/wire deformation from the first test done (no ligation).

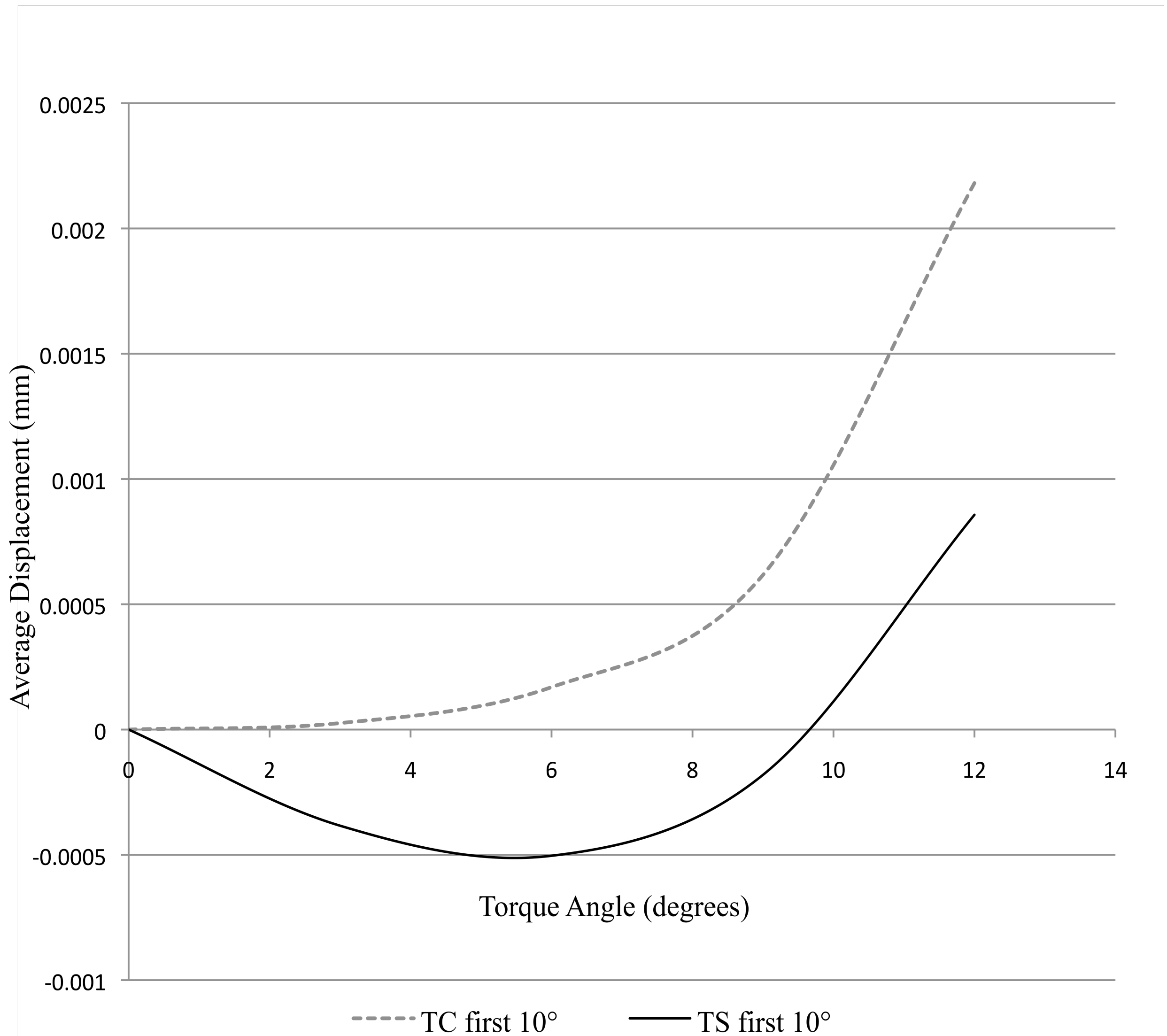
3.4.3 Engagement angle

According to Meling *et al*[21] an engagement angle of 7.2° is expected for a 0.019 × 0.025-in wire in a 0.022-in slot bracket. However, for clinical purposes, this amount of engagement angle more formally depends upon the initial wire/slot third-order angle before inserting the wire into the bracket slot[6]. However, this initial angle is almost impossible to measure or know clinically, likewise the engagement angle in the adjacent brackets. Meling *et al*[22] also noted, that any moment in the mesial-distal direction (second order moment) exerted on a bracket would reduce, if not eliminate, the engagement angle between an archwire and a bracket even though, clinically speaking it is common to apply torque to a bracket that also has a second-order moment. In short, in clinical situations it is problematic, if not impossible, to identify the amount of engagement angle involved.

Huang *et al*[9] in their finite element analysis, tried to more closely mimic a clinical setting so as to measure the torque and play angle for different bracket systems. They describe some characteristic “bends” in their resulting moment-torque activation curves, where the first bend represents the engagement angle (7.5° for a 0.019 × 0.025-in wire). Similarly, in our experiment, upon loading, this bend in the graph of torque versus angle of wire twist is 8° for DC and about 9° for TC. However, for TS and DS there is a more immediate engagement observed and torque as the wire rotates in the bracket slot. The initial engagement in this instance is due to the effects of steel ligation with measured moments higher than 5 Nmm at 3°–6° for TS and DS (Table 3.1).

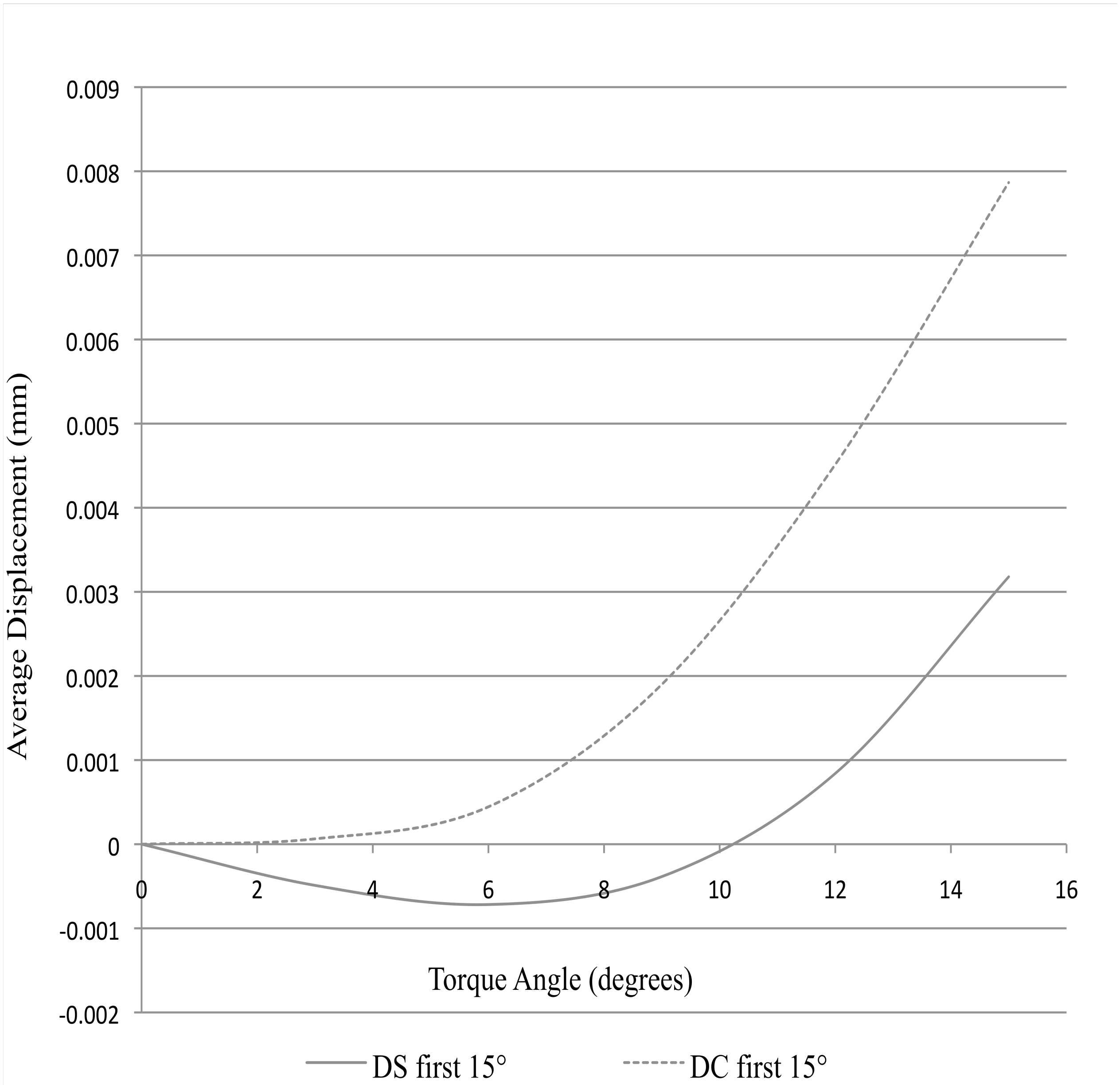
The previously reported engagement angle for Damon Q brackets (with the same type and size of bracket/archwire used in our experiment) was 10.5 ± 1.5°[19]. The initial engagement angle for the group with steel ties measured in this work is as low as 3°; thus, the engagement has been reduced by almost 7° (from initial bracket engagement to initial ligature engagement). Although wire ligation with Damon brackets is not common clinical practice, the result of the present study suggest that SS wire ligation would result in improved torque at low degrees of wire rotation.

It is interesting to note that before the wire engages the bracket slot walls, there is a small amount of reduction in the width of the bracket slot (see Figures 3.6A and 3.6B) for TS and DS.



A

Figure 3.7A First 10° of loading of wire twist: relative deformation versus angle of wire twist for Twin Orthos conventionally ligated with elastic ties and Twin Orthos brackets ligated with stainless steel ties.



B

Figure 3.7B First 15° of loading of wire twist: relative deformation versus angle of wire twist for Damon Q brackets conventionally ligated and Damon Q brackets ligated with stainless steel ties.

This suggests that the slot walls after ligation actually slightly deform inwards due to the tight steel tie as it pushed against the wire at one end and pulls the tie wings together at the other end (see Figure 3.3 A). This reduction in slot width should in theory lead to a possible reduction in the engagement angle. The reduction in slot width will depend upon the amount of ligation force when the bracket is ligated and the type of the bracket material. Although torque was higher for the steel ligated brackets for the first 10° of wire torsion, this increase is probably due to ligature engagement rather than the reduction in the slot width. In our experiment the measured reduction in the slot width was about 0.5 μm, which the clinical relevance of this small magnitude is questionable. Nevertheless, it is important to think of the role of stainless steel ligation clinically in possibly reducing the slot width for previously torqued brackets (plastically deformed) that are undergoing additional torque application.

From an inspection of the final 25° of wire twist in our unloading graphs for torque *vs*. wire twist (Table 3.1). It is obvious that torque are close to zero at 15° for TC and at 12° for the remainder of the groups considered (DC, DS, TS). These new angles of 15° for TC and 12° for (DS, DC, and TS) are the new engagement angles for future torque application, which add about an extra 7° (TC) and 4° (DC) from the initial engagement angles. This increase in engagement angle should be taken into consideration when a clinician applies torque to a pre-torqued bracket. Bracket deformation and the increase in engagement angle can be an argument against any form of bracket recycling[18]. In fact, bracket deformation is a significant factor that contributes to different torque expressions, the detailed discussion of which forms the basis of the next chapter.

It is important to note that all of our findings were specific to certain wire/bracket relationships (*i.e.*, 0.019 × 0.025-in stainless steel in 0.022 × 0.028-in bracket). Using different wire or bracket sizes may result in different findings. Although Hirai and co-workers[10] noticed an increase in torque in going from elastic ligated brackets to steel ligated brackets using equivalent wire and bracket sizes to our experiment, they noticed no difference between these groups when using 0.021 × 0.028-in stainless steel in a 0.022-in slot. Looking into the effects of steel ligation on different bracket/wire size combinations forms the basis of future investigations by our research group.

It is also important to understand that this study did not evaluate the role of wire deformation in torque during both loading and unloading. Upon wire torsion inside the bracket slot, there will be an increase in the stress that is located on the outside surface of the wire[23]. This increase in stress in the outer layer, at the corner or edges of the wire, combined with the relatively small cross-section of the wire used is enough to result in some wire deformation. This deformation can be significant to affect torque and can possible differ depending on the type and design of the brackets[5]. Clinically, wire deformation whether due to mechanical stresses applied by the clinician, or functional forces from a patient chewing, can

also play an interesting role in the variation of torque expression. This interesting topic may lead to possible further investigation in the near future.
Moreover, temperature variation and the chemical alteration of metal properties in a patient's mouth may also have some effect on the performance of a bracket or archwire, and therefore, on torque expression. These physical or chemical effects are also worthy of further pursuit.

The source of error in this experiment are related to two sources: the apparatus used as well as the methodology followed. The apparatus measurement error has been previously reported by Badawi et al[4] for the force/torque load cell at full range at 1.5%, and for the inclinometer (360° rotation range) with 0.05° resolution. The overhead camera measurement error is related to the accuracy of the image correlation process that was reported before by Lacoursiere et al[13] at 0.15μm. The errors related to the methodology are associated with bracket mounting errors, the sandblasting process and the force of SS ligature ties. Mounting variations, such as variations in the thickness of the glue layer securing the bracket base to the bracket holder, could affect the vertical distance between the bracket slot and the load cell (Δz). We attempted to standardize the thickness of this adhesive layer was through the use of a custom-fabricated rigid mounting jig to mount all brackets, thereby maintaining consistency in bracket placement on the load cells and minimizing the error. With this mounting process being used uniformly for all brackets in all groups, the potential for measurement error due to bracket positioning variations expected to be small, however a potential of errors is acknowledged; using a sensitivity analysis, it was found that a thickness variation of 0.5mm could lead to 20% error on very small torque levels (0.85Nmm) seen at low rotational angles (9°), but in the order of less than 1% for larger torque values (94Nmm) seen at high rotation angles (45°). The sandblasting process may have some effects on the physical properties of the bracket superficial layer, However, since all the brackets used in all study groups were subjected to the same process using the same equipment, the potential impact of this step on comparative analyses between the groups should be negligible. The steel ligation was placed by one operator and the force of ligation was not measured, and this would resemble a clinical situation where ligation forces are not measured.

3.5 Conclusions

The goal of this study was to investigate the effects of SS ligation on the mechanical characteristics of conventional Orthos twin brackets and self-ligated Damon Q brackets subjected to torque. The following conclusions can be stated:

(1) SS ties increase torque for conventional Twin brackets (Orthos). However, steel ligation did not make a difference for self ligated brackets (Damon Q).

(2) Stainless steel ligature ties resulted in a more immediate torque in Twin brackets (Orthos) than did the conventionally ligated self ligating (Damon Q) and Twin (Orthos) brackets.

(3) Torsion forces are sufficient to cause plastic deformation to all brackets.

(4) Damon Q brackets exhibit less bracket deformation than Orthos twin brackets.

(5) Stainless steel ties can play an important role in reducing the amount of plastic deformation for both types of brackets; however, the clinical relevance of such a reduction is questionable.

3.6 Bibliography

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Chapter Four

Elastic and plastic orthodontic bracket deformation associated with stainless steel ligation

4.1 Introduction

In order to produce the proper buccal-lingual root angulations of a tooth, a third-order bend (twist) is applied to a rectangular wire when it is inserted into a bracket slot. In a contemporary appliance the bracket slot is cast at an angle relative to the bracket base, termed the prescription of the bracket. Ideally, insertion of a straight wire will generate a moment (torque expression) of sufficient magnitude to achieve the desired root alignment of a tooth[1]. However, in many cases, applied finishing bends or additional twists need to be added to the archwire in order to accommodate variations in a patient's anatomical tooth structure, treatment needs, or other mechanical challenges[2, 3]. These mechanical challenges are sometimes related to manufacturing tolerances in bracket slot dimensions[4]. Bracket deformation (elastic and plastic) with wire rotation may also result in reduced torque expression[5]. Plastic deformation of a bracket will permanently change the slot dimension, possibly resulting in increased theoretical torque play (*i.e.*, wire rotation in the slot with no torque expression) and decreased torque of a bracket[6] with multiple torque applications.

The magnitude of bracket deformation can be related to bracket design and composition, as well as the archwire material and geometry, and the magnitude and duration of the applied force. Most of the bracket deformation described in the literature is related to changes in the gingival-occlusal dimension of the bracket slot, from here on referred to as the bracket or slot width.

Metals will elastically deform and fully recover when loaded below the yield point. When the load passes the yield point the metal will have unrecoverable plastic deformation. The elastic and plastic deformations of a structure will depend on the geometry of this structure and the applied loads. Moreover, when metals are plastically deformed this results in local changes to the property of the metal structure (strain hardening or work hardening) and physical propoerties[7]. The process of surface work hardening increases the surface hardness of the material[8]. The material resistance to indentation measures material hardness[9]. As wire rotates and engages into the bracket's slot walls, it may result in a surface indentation. Depending on the hardness of the bracket material and how much work hardening has occurred to the slot walls, the resistance to notching may vary.

Most of the published literature regarding bracket deformation compares ceramic or polycarbonate brackets to stainless steel (SS) brackets. SS brackets are arguably considered by many researchers in the field of orthodontics to be the gold standard in terms of bracket deformation[10].

Ligation methods have been extensively researched and discussed in terms of their effects on the resistance to sliding. However, few studies have described the effects of ligation on bracket deformation. Major *et al.*[11] compared the differences in bracket deformation between active and passive self-ligated brackets. They assumed that the door used for ligation of the bracket plays a role in holding the wings of the bracket together. They reported that deformations observed for Speed brackets were almost 14 times more extensive as for In-Ovation R (GAC, Bohemia, NY) brackets. One of the reasons given for these differences is the fact that the door in Speed brackets opens during the torque experiment, therefore failing to prevent the deformation of the slot walls.

Melenka *et al.*[12] compared the deformation between SS and titanium brackets and reported that ligation could affect the positioning of the wire into the slot of the bracket. This would in turn affect bracket deformation. They described the slot wall as being similar to a leaver arm in which the further from the base that the force is applied, the more deflection is achieved. Consequently, if ligation is able to position the wire closer to the base, then, in theory, there should be less deformation. Gioka *et al.*[13] mention that steel ligature would actually "diminish slot-wire clearance", which would mean some kind of deformation of the bracket, but they provide no further explanation as to how this could happen.

Although, in our discussion in Chapter 3 it was described how SS ligation would in fact reduce the bracket slot width upon ligation and reduce the overall deformation (slot width increase), no evaluation was done to describe all the other effects of SS ligation on bracket deformation, such as notching of slot walls, and the significance of these effects. No current published research reports in details the effect of the SS ligation method on bracket deformation.

The objective of this study was to evaluate the effect of SS ligation on local bracket deformation associated with the application of torque moment in a conventional twin SS bracket and a self-ligating stainless steel bracket.

4.2 Materials and method

The present study utilized 60 upper right central incisor Damon Q® 0.022 × 0.028-in (0.56 × 0.71 mm) SS slots, with 15° torque and 5° tip prescription (Ormco Corporation, Orange, California, USA) and 60 upper right central incisor Ormco Orthos® twin brackets with 0.022 × 0.028-in (0.56 × 0.71 mm) SS slots, 15° torque, and 5° tip prescription (Ormco Corporation, Division of Sybron, Orange, CA). The Damon Q® bracket group was subdivided into 30 brackets ligated with SS wire (DS group) and 30 ligated with the sliding bracket door (DC group). The Ormco Orthos® twin bracket group was subdivided into 30 brackets ligated with SS wire (TS group) and 30 ligated with elastic ties (TC group). Using the method previously described by Major *et al.*[6, 11, 14] the brackets were lightly sandblasted, utilizing Ortho Technology TruEtch (50 micron aluminum oxide, item number 12300, The Arum group, Spokane, WA, USA)[15] to reduce the surface reflectivity and then glued onto SS cylinders (bracket holders) with an epoxy adhesive (Loctite, E-20HP; Hysol, Henkel, Rocky Hill, CT, USA)[6]. Before commencing the experiment, a profile image was taken of the bracket slot with a digital single-lens reflex camera (Canon EOS-D10 10D, Tokyo, Japan). The bracket with the holder was then placed into the torquing apparatus. The apparatus and description of the procedures used in this study are explained elsewhere[6, 11, 14].

Upon completing the torque testing procedures, a second profile image of the bracket slot was taken using the same camera settings, distance, and alignment used as for the first profile image. The profile images were calibrated and processed with computer software (DaVis 7.2, LaVision GmbH DaVis 7.2, Göttingen, Germany, 2007)[16]. For each second profile image taken (after torque profile image), 10 points are selected, where each sequence of five points selected form a line that represents the right hand slot wall and the base wall of the bracket slot (see Figure 4.1). Along the right hand slot wall of the bracket slot, the second point selected represents the point at which the archwire edge engages into the right hand slot wall and the load is applied (identified by the physical indentation caused by the archwire on the slot wall). A program was written using computer software Matlab (The Mathworks Inc., Natick, MA, USA) to measure the distance (mm) of the wire edge/bracket wall contact point to the base of the bracket slot for the profile images. The program utilizes a two-dimensional (x,y) coordinate system for selecting points on the profile images and measuring distance between these points. The distance between this second point (point of load application) and the point of intersection of the right hand slot wall with the base of the slot is measured (mm).

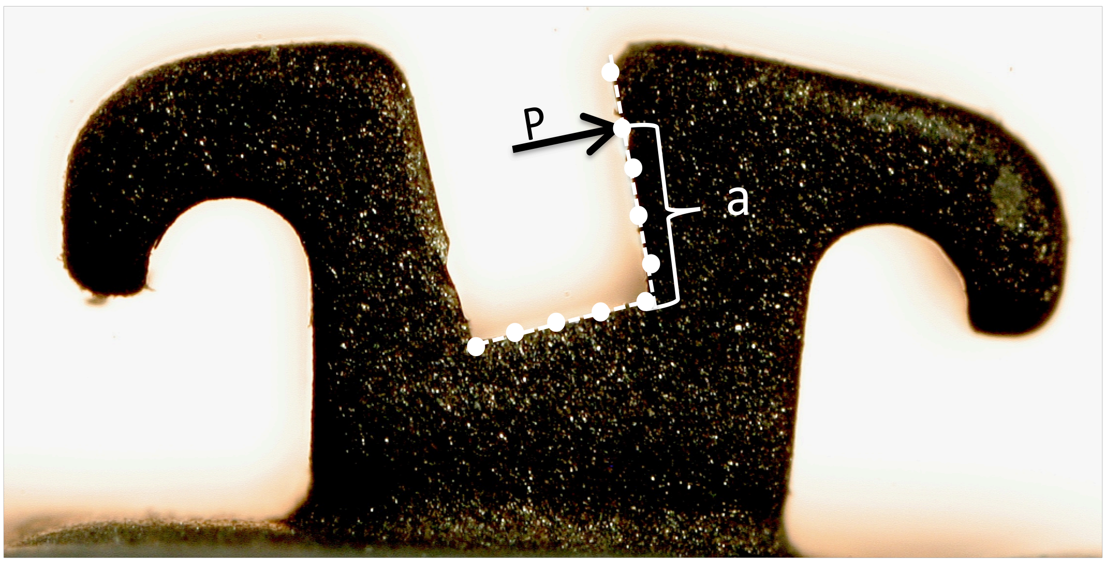


Figure 4.1 Profile images of Orthos twin bracket showing the five points selected on the right slot wall and bottom of the slot surfaces to outline the slot walls. P: the point of load application in which the archwire edge contacts the slot wall, a: the distance (mm) of this contact point to the intersection point at the base of the slot.

Torque measurements were obtained for all four groups using 0.019 × 0.025-in SS wire (Ormco, Orange, CA, USA), where new wire was used for every bracket. Torque moment (Nmm) measurements were obtained at 3° increments of wire rotation from 0° up to 45°, and back again to 0°. In total, data were collected for 32 stages of wire rotation. Overhead images from a high-resolution chargecoupled device camera (piA2400-12 gm, 2448 × 2050 pixels, 8 bit, grey scale, Basler Vision Technologies, Exton, PA, USA)[12] were also obtained for each stage of wire rotation. The images were also processed (DaVis 7.2, LaVision GmbH DaVis 7.2, Göttingen, Germany, 2007) using a correlation map to create a displacement vector field image showing the dimensional changes (mm) in the width of the bracket. A new custom code was written with Matlab (The Mathworks Inc., Natick, MA, USA) to assess the mass displacement of the bracket's width for these overhead images[15].

A statistical package (SPSS 19.0, Chicago, IL, USA) was used to carry out repeated measures ANOVA and MANOVA in order to answer the objective of this study from the overhead images. Normality of the data can be assumed from the box-plot and Kolmogorov-Smirnov test. The equal variance cannot be assumed. Therefore, Brown-Forsythe and Welch statistical analysis methods were used to assess the significance at all angles. *Post hoc* multiple comparisons between the groups using Tamhane tests were carried out at each angle. Because a four comparisons (TS vs. TC, DS vs. DC, TS vs. DC and TS vs. DS) have been done, the level of significance considered was Bonferroni-corrected significance level of 0.05/4 = 0.012 ($p < 0.012$).

One-way ANOVA was performed to find the statistical difference between all groups for the distance of the wire edge/bracket wall contact point to the base of the bracket slot of the profile image data set. To assess the intra-examiner reliability, the distance of the point of load application was re-measured on ten brackets over three separate times, and intraclass correlation coefficient (ICC) was calculated. The ICC value was 0.89% which indicate a good intra-rater reliability.

4.3 Results

Nine brackets of the Orthos twin bracket ligated with elastic ties group (TC) and three of the Damon Q ligated with conventional sliding door group (DC) had to be eliminated from the overhead image data as some of the image files were missing at certain measuring points due to user error. The descriptive statistic of the means of overhead image bracket slot width changes (bracket deformation values, mm) for the 32 wire rotation angles (degrees), and the standard deviation for all brackets are presented in Table 4.1.

Table 4.1. Bracket width displacements (mm) per angle of twist (°) according to bracket type and ligation method with their standard deviation in parenthesis.

	Torque Angle°	Displacement Means (mm) and SD			
		TS (SD)	TC (SD)	DS (SD)	DC (SD)
Loading	0	0.0000 (0.0000)	0.0000 (0.0000)	0.0000 (0.0000)	0.0000 (0.0000)
	3	−0.0004 (0.0004)	0.0000 (0.0001)	−0.0005 (0.0004)	0.0001 (0.0005)
	6	−0.0005 (0.0006)	0.0002 (0.0002)	−0.0007 (0.0007)	0.0004 (0.0008)
	9	−0.0002 (0.0012)	0.0006 (0.0007)	−0.0004 (0.0011)	0.0019 (0.0015)
	12	0.0008 (0.0020)	0.0022 (0.0012)	0.0008 (0.0015)	0.0045 (0.0021)
	15	0.0026 (0.0027)	0.0046 (0.0015)	0.0032 (0.0018)	0.0079 (0.0025)
	18	0.0050 (0.0032)	0.0074 (0.0018)	0.0062 (0.0020)	0.0117 (0.0028)
	21	0.0078 (0.0037)	0.0106 (0.0022)	0.0097 (0.0021)	0.0157 (0.0030)
	24	0.0108 (0.0041)	0.0142 (0.0025)	0.0132 (0.0023)	0.0199 (0.0031)
	27	0.0142 (0.0046)	0.0183 (0.0029)	0.0168 (0.0025)	0.0242 (0.0033)
	30	0.0178 (0.0052)	0.0228 (0.0034)	0.0203 (0.0026)	0.0286 (0.0037)
	33	0.0217 (0.0059)	0.0280 (0.0041)	0.0238 (0.0027)	0.0330 (0.0039)
	36	0.0259 (0.0067)	0.0339 (0.0051)	0.0272 (0.0029)	0.0374 (0.0041)
	39	0.0301 (0.0076)	0.0404 (0.0064)	0.0304 (0.0031)	0.0416 (0.0043)
	42	0.0345 (0.0086)	0.0476 (0.0082)	0.0332 (0.0032)	0.0455 (0.0046)
	45	0.0388 (0.0097)	0.0557 (0.0108)	0.0358 (0.0034)	0.0490 (0.0050)
Unloading	45	0.0391 (0.0098)	0.0561 (0.0109)	0.0359 (0.0034)	0.0491 (0.0051)
	42	0.0388 (0.0096)	0.0551 (0.0109)	0.0354 (0.0034)	0.0481 (0.0051)
	39	0.0382 (0.0095)	0.0540 (0.0106)	0.0346 (0.0033)	0.0468 (0.0051)
	36	0.0372 (0.0093)	0.0524 (0.0103)	0.0335 (0.0032)	0.0452 (0.0050)
	33	0.0359 (0.0090)	0.0503 (0.0101)	0.0319 (0.0031)	0.0428 (0.0050)
	30	0.0341 (0.0087)	0.0475 (0.0100)	0.0295 (0.0030)	0.0393 (0.0049)
	27	0.0317 (0.0085)	0.0444 (0.0099)	0.0262 (0.0030)	0.0349 (0.0046)
	24	0.0291 (0.0082)	0.0408 (0.0096)	0.0220 (0.0030)	0.0297 (0.0043)
	21	0.0261 (0.0078)	0.0366 (0.0093)	0.0174 (0.0030)	0.0238 (0.0040)
	18	0.0223 (0.0075)	0.0321 (0.0093)	0.0127 (0.0030)	0.0180 (0.0039)
	15	0.0182 (0.0067)	0.0279 (0.0086)	0.0076 (0.0026)	0.0119 (0.0032)
	12	0.0169 (0.0062)	0.0270 (0.0085)	0.0054 (0.0017)	0.0084 (0.0025)
	9	0.0167 (0.0062)	0.0269 (0.0085)	0.0052 (0.0014)	0.0077 (0.0021)
	6	0.0166 (0.0063)	0.0269 (0.0085)	0.0052 (0.0014)	0.0075 (0.0022)
	3	0.0166 (0.0063)	0.0268 (0.0085)	0.0052 (0.0013)	0.0074 (0.0021)
	0	0.0167 (0.0063)	0.0268 (0.0085)	0.0050 (0.0013)	0.0073 (0.0021)

TS: Orthos Twin with stainless steel ligation, TC: Orthos twin with conventional elastic ligation, DC: Damon Q with conventional sliding door, and DS: Damon Q with stainless steel ligation in addition to the sliding door.

The descriptive statistics of the distance of the point of load application (mm) from the profile images is provided in Table 4.2. The differences between all bracket displacements (mm) averaged over all angles for the overhead images are provided in Table 4.3. Overall, the change in bracket slot width was significantly different ($p < 0.001$) between all four groups.

Table 4.2. Mean, standard deviation, maximum, and minimum for the distance (mm) of the load application point in all second profile images bracket groups.

Bracket Type	N	Mean	SD	Minimum	Maximum
TS	30	.4710	.0218	0.370	0.490
TC	30	.5133	.0195	0.490	0.580
DS	30	.4787	.0103	0.460	0.500
DC	30	.5185	.0207	0.487	0.550

Table 4.3. Pairwise comparisons of averaged slot width displacement (mm) from the overhead images for all bracket groups.

Bracket Type (I)	Bracket Type (J)	Mean Difference (I − J)	Std. Error	P-value	95% Confidence Interval for Difference	
					Lower Bound	Upper Bound
DC	TS	0.003	0.001	0.037	0	0.007
	DS	0.007	0.001	<0.001	0.004	0.01
DS	TS	−0.003	0.001	0.017	−0.007	0
TC	DS	0.012	0.001	<0.001	0.009	0.015
	DC	0.005	0.001	0.001	0.002	0.009
TS	TC	−0.009	0.001	<0.001	−0.012	−0.005

TS: Orthos Twin with stainless steel ligation, TC: Orthos twin with conventional elastic ligation, DC: Damon Q with conventional sliding door, and DS: Damon Q with stainless steel ligation in addition to the sliding door.

The *post hoc* multiple comparisons identified that the Twin brackets having wire ligatures (TS) had significantly ($p < 0.012$) less deformation (increase in bracket width) than Twin brackets with elastic ligatures (TC) at all angles with the exception of 9° to 12° (Table 4.4). Similarly, the Damon Q having wire ligatures (DS) showed significantly ($p < 0.001$) less deformation than the DC-type brackets at all angles (Table 4.5).

TS brackets showed no significant deformation differences ($p>0.012$) in comparison to DS and significantly ($p< 0.012$) less deformation to DC brackets from 0° to 33° of the unloading, then TS had significantly ($p<0.012$) more deformation than DC and DS for the last (15° to 0°)and (27° to 0°) respectively of the unloading angles (table 4.6 and 4.7).

Table 4.4. Comparison of bracket displacement (mm) between Twin Orthos with steel ties and Twin Orthos with elastic ties.					
	Torque Angle (°)	Mean Difference (TS − TC)	P-value	95% Confidence Interval	
				Lower Bound	Upper Bound
Loading Angles (ascending)	0	0	0	0.000	0.000
	3	-0.000	<0.0001	-0.001	-0.000
	6	-0.001	<0.0001	-0.001	-0.000
	9	-0.001	0.026	-0.002	-0.000
	12	-0.001	0.018	-0.003	-0.000
	15	-0.002	0.011	-0.004	-0.000
	18	-0.002	0.008	-0.004	-0.000
	21	-0.003	0.006	-0.005	-0.001
	24	-0.003	0.004	-0.006	-0.001
	27	-0.004	0.002	-0.007	-0.001
	30	-0.005	0.001	-0.008	-0.002
	33	-0.006	<0.0001	-0.010	-0.002
	36	-0.008	<0.0001	-0.013	-0.003
	39	-0.010	<0.0001	-0.016	-0.005
	42	-0.013	<0.0001	-0.020	-0.007
	45	-0.017	<0.0001	-0.025	-0.009
Unloading Angles (descending)	45	-0.017	<0.0001	-0.025	-0.009
	42	-0.016	<0.0001	-0.025	-0.008
	39	-0.016	<0.0001	-0.024	-0.008
	36	-0.015	<0.0001	-0.023	-0.007
	33	-0.014	<0.0001	-0.022	-0.007
	30	-0.013	<0.0001	-0.021	-0.006
	27	-0.013	<0.0001	-0.020	-0.005
	24	-0.012	<0.0001	-0.019	-0.005
	21	-0.011	0.001	-0.017	-0.004
	18	-0.010	0.002	-0.017	-0.003
	15	-0.010	0.001	-0.016	-0.003
	12	-0.010	<0.0001	-0.016	-0.004
	9	-0.010	<0.0001	-0.016	-0.004
	6	-0.010	<0.0001	-0.016	-0.004
	3	-0.010	<0.0001	-0.016	-0.004
	0	-0.010	<0.0001	-0.016	-0.004

Table 4.5. Comparison of bracket displacement (mm) between Damon Q bracket with steel ligation (DS) and Damon Q bracket conventionally ligated (DC) at each collection angle.

	Torque Angle (°)	Mean Difference (DS − DC)	P-Value	95% Confidence Interval	
				Lower Bound	Upper Bound
Loading Angles (ascending)	0	0	0	0.000	0.000
	3	-0.001	<0.0001	-0.001	-0.000
	6	-0.001	<0.0001	-0.002	-0.001
	9	-0.002	<0.0001	-0.003	-0.001
	12	-0.004	<0.0001	-0.005	-0.002
	15	-0.005	<0.0001	-0.006	-0.003
	18	-0.005	<0.0001	-0.007	-0.004
	21	-0.006	<0.0001	-0.008	-0.004
	24	-0.007	<0.0001	-0.009	-0.005
	27	-0.007	<0.0001	-0.010	-0.005
	30	-0.008	<0.0001	-0.011	-0.006
	33	-0.009	<0.0001	-0.012	-0.007
	36	-0.010	<0.0001	-0.013	-0.008
	39	-0.011	<0.0001	-0.014	-0.008
	42	-0.012	<0.0001	-0.015	-0.009
	45	-0.013	<0.0001	-0.016	-0.010
Unloading Angles (descending)	45	-0.013	<0.0001	-0.016	-0.010
	42	-0.013	<0.0001	-0.016	-0.009
	39	-0.012	<0.0001	-0.015	-0.009
	36	-0.012	<0.0001	-0.015	-0.009
	33	-0.011	<0.0001	-0.014	-0.008
	30	-0.010	<0.0001	-0.013	-0.007
	27	-0.009	<0.0001	-0.012	-0.006
	24	-0.008	<0.0001	-0.010	-0.005
	21	-0.006	<0.0001	-0.009	-0.004
	18	-0.005	<0.0001	-0.008	-0.003
	15	-0.004	<0.0001	-0.006	-0.002
	12	-0.003	<0.0001	-0.004	-0.001
	9	-0.002	<0.0001	-0.004	-0.001
	6	-0.002	<0.0001	-0.004	-0.001
	3	-0.002	<0.0001	-0.004	-0.001
	0	-0.002	<0.0001	-0.004	-0.001

Table 4.6. Comparison of bracket displacement (mm) between Orthos Twin brackets ligated with steel ligation (TS) and Damon Q bracket conventionally ligated (DC) at each collection angle (°).

	Torque Angle (°)	Mean Difference (TS-DC)	P-Value	95% Confidence Interval	
				Lower Bound	Upper Bound
Loading Angles (ascending)	0	0	0	0.000	0.000
	3	0.000	0.002	0.000	0.000
	6	-0.001	<0.0001	-0.001	-0.000
	9	-0.002	<0.0001	-0.003	-0.001
	12	-0.004	<0.0001	-0.005	-0.002
	15	-0.005	<0.0001	-0.007	-0.003
	18	-0.007	<0.0001	-0.009	-0.004
	21	-0.008	<0.0001	-0.01	-0.005
	24	-0.009	<0.0001	-0.011	-0.006
	27	-0.010	<0.0001	-0.012	-0.007
	30	-0.011	<0.0001	-0.014	-0.007
	33	-0.011	<0.0001	-0.014	-0.007
	36	-0.012	<0.0001	-0.015	-0.007
	39	-0.011	<0.0001	-0.016	-0.007
	42	-0.011	<0.0001	-0.016	-0.006
	45	-0.010	<0.0001	-0.016	-0.004
Unloading Angles (descending)	45	-0.010	<0.0001	-0.015	-0.004
	42	-0.009	<0.0001	-0.015	-0.004
	39	-0.009	<0.0001	-0.014	-0.003
	36	-0.008	0.001	-0.013	-0.003
	33	-0.007	0.005	-0.012	-0.002
	30	-0.005	0.042	-0.010	-0.000
	27	-0.003	0.405	-0.008	0.001
	24	-0.001	0.999	-0.005	0.004
	21	0.002	0.653	-0.002	0.006
	18	0.004	0.049	0.000	0.008
	15	0.006	<0.0001	0.002	0.010
	12	0.009	<0.0001	0.005	0.012
	9	0.009	<0.0001	0.005	0.012
	6	0.009	<0.0001	0.006	0.012
	3	0.009	<0.0001	0.006	0.013
	0	0.009	<0.0001	0.006	0.013

Table 4.7. Comparison of bracket displacement (mm) between Twin Orthos ligated with steel ligation (TS) and Damon Q bracket ligated with steel ligation at each collection angle (°).

	Torque Angle (°)	Mean Difference (TS-DS)	P-Value	95% Confidence Interval	
				Lower Bound	Upper Bound
Loading Angles (ascending)	0	0	0	0.000	0.000
	3	0.000	0.883	-0.000	0.000
	6	0.000	0.774	-0.000	0.001
	9	0.000	0.992	-0.001	0.001
	12	0.000	1.000	-0.001	0.001
	15	-0.001	0.913	-0.002	0.001
	18	-0.001	0.385	-0.003	0.001
	21	-0.002	0.091	-0.004	0.000
	24	-0.002	0.045	-0.005	0.000
	27	-0.003	0.055	-0.005	0.000
	30	-0.002	0.133	-0.005	0.000
	33	-0.002	0.419	-0.005	0.001
	36	-0.001	0.883	-0.005	0.002
	39	0.000	1.000	-0.004	0.004
	42	0.001	0.973	-0.003	0.006
	45	0.003	0.516	-0.002	0.008
Unloading Angles (descending)	45	0.003	0.472	-0.002	0.008
	42	0.003	0.391	-0.002	0.009
	39	0.004	0.313	-0.002	0.009
	36	0.004	0.238	-0.001	0.009
	33	0.004	0.153	-0.001	0.009
	30	0.005	0.063	0.000	0.009
	27	0.006	0.009	0.001	0.010
	24	0.007	<0.0001	0.003	0.011
	21	0.009	<0.0001	0.004	0.013
	18	0.010	<0.0001	0.006	0.014
	15	0.011	<0.0001	0.007	0.014
	12	0.012	<0.0001	0.008	0.015
	9	0.011	<0.0001	0.008	0.015
	6	0.011	<0.0001	0.008	0.015
	3	0.011	<0.0001	0.008	0.015
	0	0.012	<0.0001	0.008	0.015

Looking at the graphs of the average bracket displacements measured with overhead images (Figures 4.2A and B), both groups of brackets show similar shaped curves. The steel ligated brackets in both groups experienced a decrease in slot width for the first 10° of wire twist. After 10°, in both groups, there is a continuous increase in the slot width as the degree of wire twist increases. Upon unloading, the slot width decreases as the angle of wire twist decreases, thus signifying some elastic and plastic deformations of the bracket slot up until the unloading angle of 13° at which point no further changes in slot width occur.

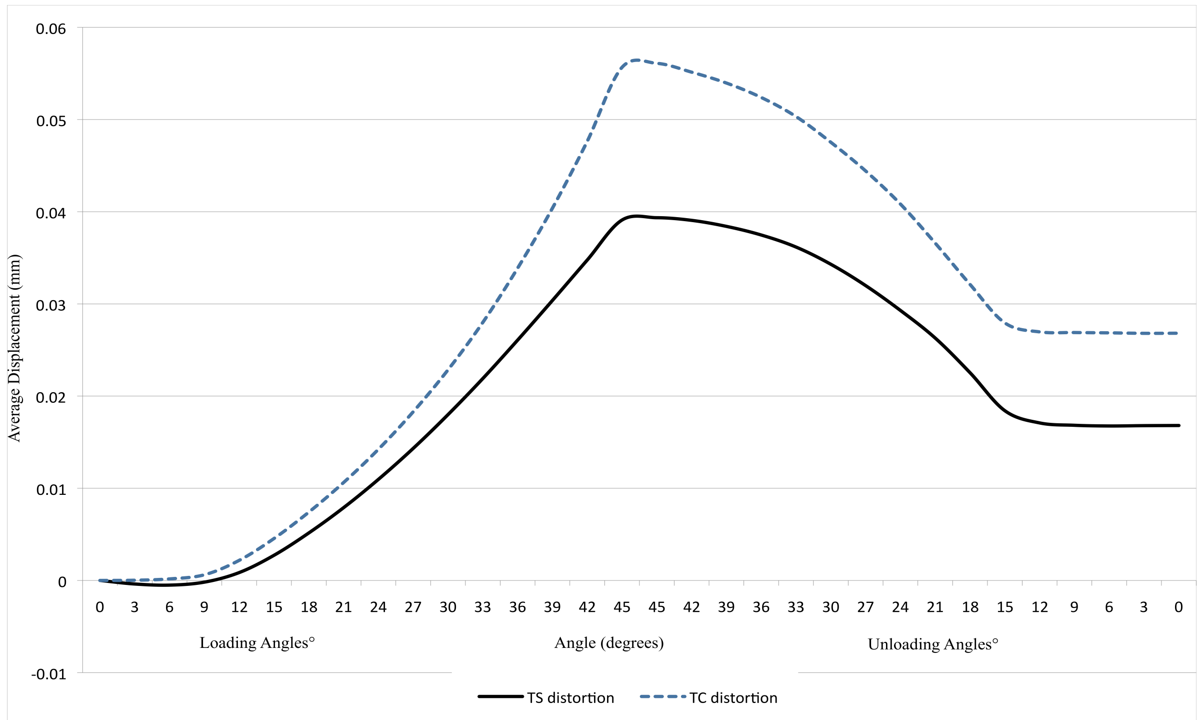
The magnitudes of plastic deformation of the brackets at completion of the experiment were: 0.0167 mm (16.7 μm) for TS, 0.026 mm (26 μm), for TC 0.005 mm (5 μm) for DS, and 0.0073 mm (7.3 μm) for DC.

The distance of the load application point was significantly ($p < 0.0001$) shorter for the SS ligated groups (DS and TS) over the conventionally ligated groups (TC and DC), Table 4.8.

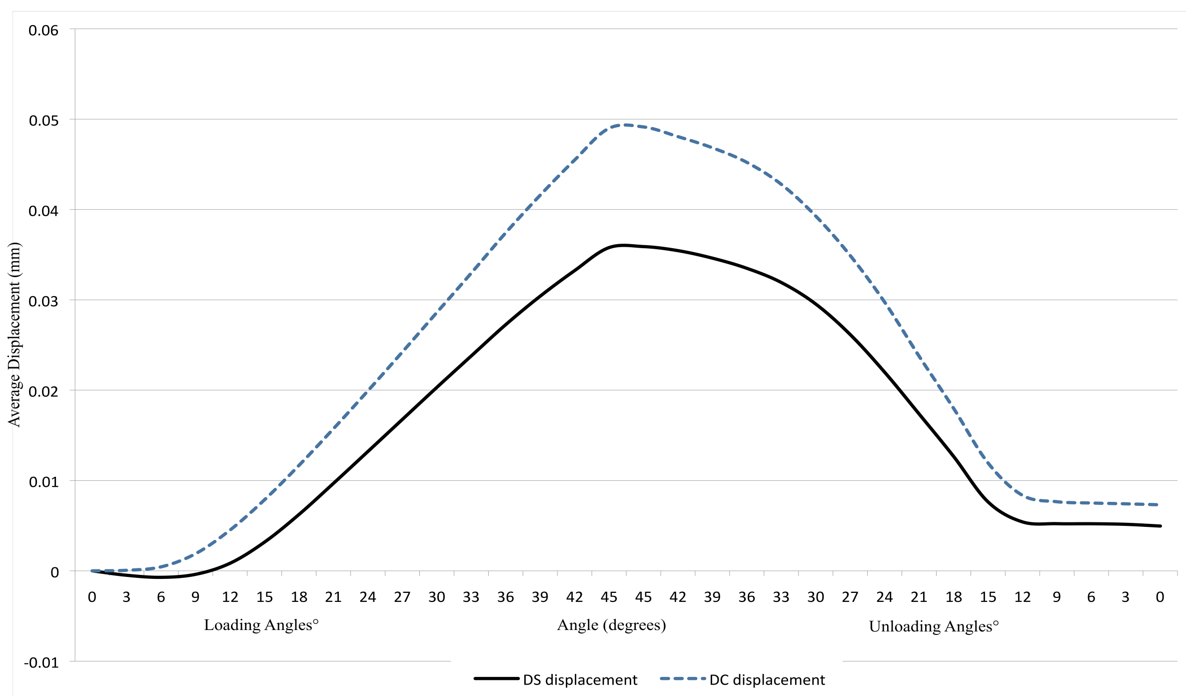
Table 4.8. Results of independent sample t-tests for the differences in the distance (mm) of the point of load application to the base of the bracket between bracket groups.

Bracket Type	Mean Difference	Sig. (P Value)	95% Confidence Interval of the Difference	
			Lower	Upper
TS vs. TC	−0.04233	<0.0001	−0.05189	−0.03277
DS vs. DC	−0.03983	<0.0001	−0.04939	−0.03027

TS: Orthos Twin with stainless steel ligation, TC: Orthos twin with conventional elastic ligation, DC: Damon Q with conventional sliding door, and DS: Damon Q with stainless steel ligation in addition to the sliding door.



A



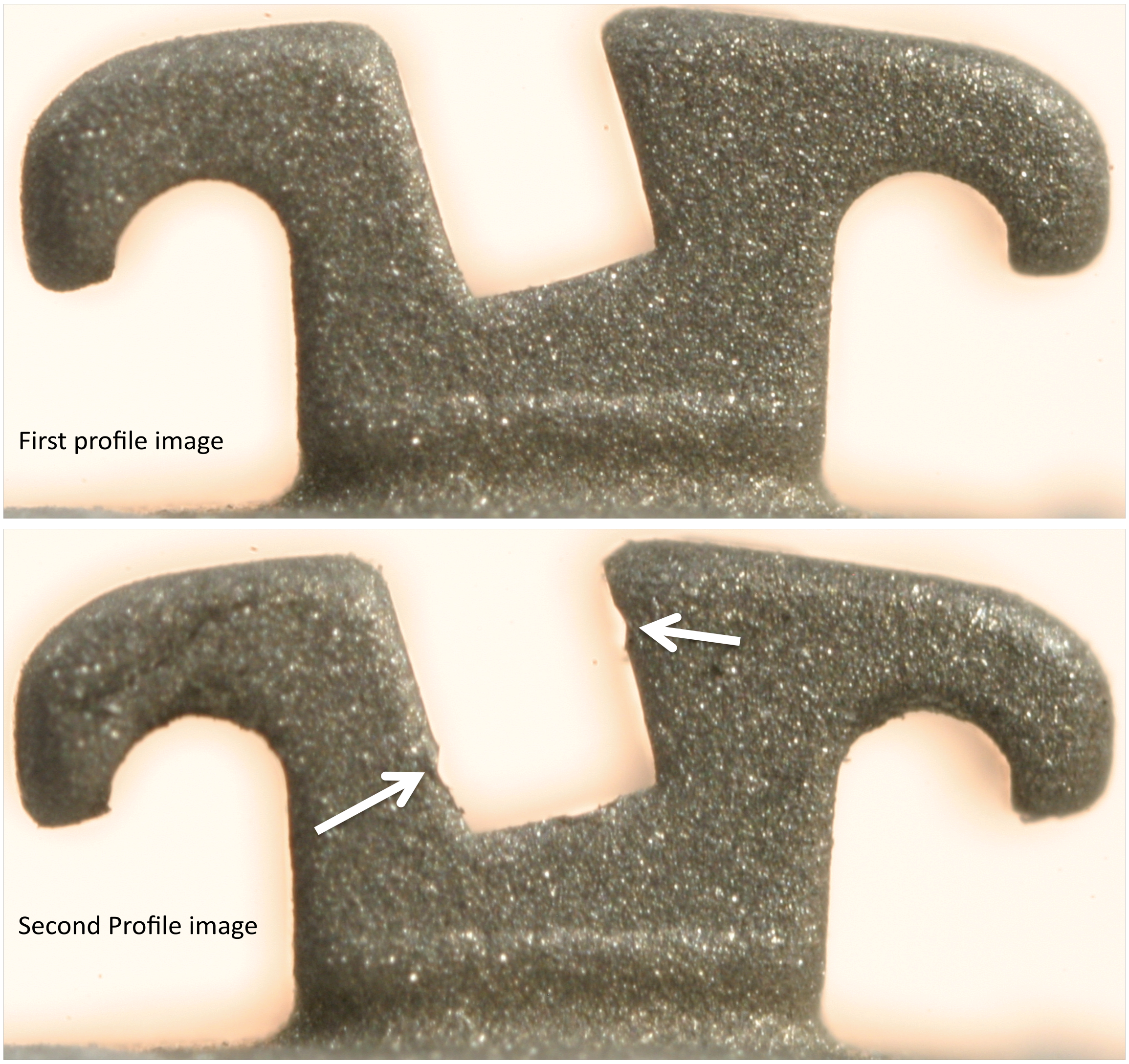
B

Figure 4.2 Average bracket width displacement (mm) per angle (°) of wire twist. A: Orthos twin with steel ligation (TS) vs. Orthos twin with elastic ties (TC); and B: Damon Q with steel ties (DS) vs. conventional Damon Q (DC).

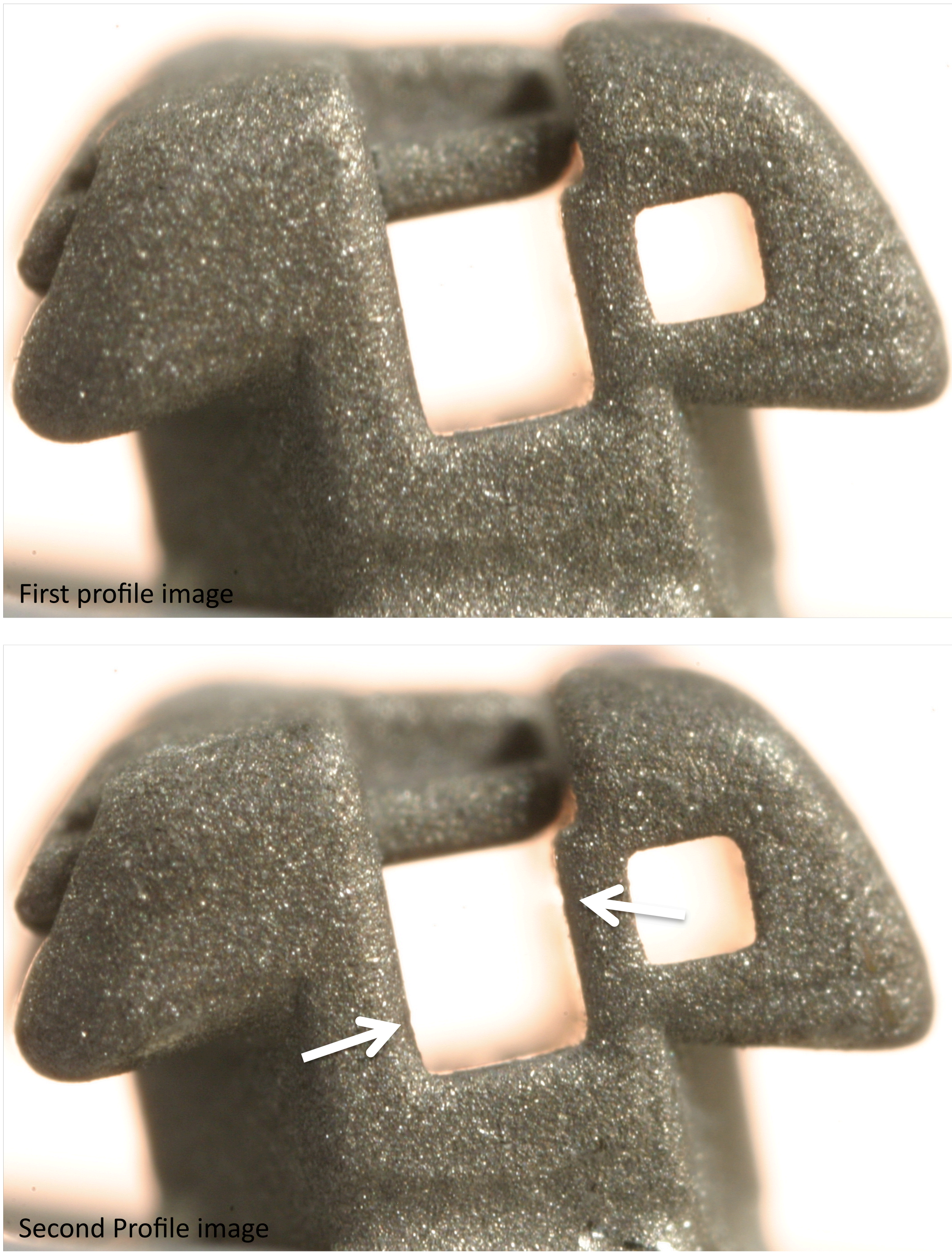
4.4 Discussion

4.4.1 Bracket elastic and plastic deformation

The purpose of this study is to evaluate the effects of steel ligation on the elastic and plastic deformation of a bracket. In fact, there is a combination of two forms of plastic deformation noted in the brackets at the end of our experiment. The first form can be expressed as permanent (plastic) changes to the slot width, and the second is local contact deformations that occur when an archwire is forced into bracket walls and causes surface indentation (notching) due to the localized contact (Hertzian) stresses[17]. The difference in bracket and wire material properties and the surface hardness have significant effects on the magnitude of bracket notching phenomena[17]. Though both types of brackets used in this experiment are made of SS, the way that each bracket is manufactured is different. Damon Q brackets are composed of "stainless steel 17-4 metal-injection-molded"[18]. This metal injection molding process, and other elements of the bracket, has an important effect on the slot walls of the bracket and therefore on the mechanical properties of the bracket, most notably an increase in surface hardness[17]. On the other hand, Orthos Twin brackets are machine milled with a "gold-based brazing" alloy to join all of the components of this SS bracket[19]. As yet, no comparison has been made in the literature regarding the surface hardness of the two types of brackets used in our experiment, and it is not clear to what extent the differences in bracket manufacturing influence the surface hardness. However, comparing the bracket notching on the bracket's walls in our samples, there is less notching (depth of indentation) on Damon Q than on Orthos twin brackets, as shown, for example, in (Figures 4.3A and B). The manufactured slot width variations between Orthos and Damon Q could contribute to the difference in notching between the two types of brackets. However, the notching differences between the two types of bracket can also be related to some other possible factors,such as, the area of contact stress in Orthos twin brackets is in fact much smaller than it is in Damon Q brackets (more of a line for Damon Q than a point for Orthos due to different bracket design) which will contribute to less notching for Damon Q than Orthos twin brackets. Moreover, the heat generated due to the “gold-based brazing” alloy to join the components of Orthos backets[19] could affect the physical property of the slot walls and make them more prone for notching. Due to all these possibilities, Orthos twin brackets sees more notching than Damon Q brackets, and therefore Damon Q probably has a better design to prevent notching.



A



B

Figure 4.3 Profile images of (A) Milled Orthos twin bracket and (B) injection molded Damon Q bracket showing first profile image (before torque applied) and second profile image (after torque applied), the arrows pointed at the notching on the slot walls. The magnitude (depth) of the notching is bigger for Orthos than it is for Damon Q brackets.

Nevertheless, it is difficult to measure this kind of deformation (notching), and therefore the significance and clinical relevance of this deformation on torque is questionable. Steel ligation has possible effects on this type of deformation. Since steel ligation provides some physical support to the tie wings of the bracket and limits the magnitude of the increase in bracket width during torque application, it is possible to see beside the increase in torque and as a side effect there is an increase in either the depth of the notching or the wire deformation.

For the alternative form of deformation that involves changes in the slot width, SS plays a different role. SS ligation will exert some seating force to seat the archwire into the bracket slot, where this seating force is higher than it is for conventionally ligated brackets with elastic ties[20]. In fact, the seating force of the steel ligation significantly ($p < 0.0001$) influences the distance from the base of the bracket slot to the point where the edge of the wire engages the tie wing or the point of load application (table 4.8). Melenka *et al.*[12] describe this distance as a lever arm, the arm is longer when the point of load application is further from the base of the slot, and consequently more deformation and less torque are expected. The role of the SS ligature in reducing the distance of load application point from the base of the slot contributes to the reduction in the bracket deformation in the steel ligated groups.

Besides the composition of the bracket, the design and geometry of the bracket also play a major role in the type of deformation associated with changes in slot width[9,15]. Twin brackets have four tie wings connected to the base of the bracket, with minimal structures to support these tie wings with more point stresses at the tie wings. In contrast, Damon Q brackets have two walls connected to a larger base. The contact area is much longer and the load is distributed and causes less point stresses. In other words, there is less structure to distort for a Twin bracket than there is for a Damon bracket. There is no literature available that describes the effects of the different design of Orthos Twin bracket *vs*. Damon Q bracket and their consequences on the deformation of the bracket. However, the fact that Orthos twin brackets are made of different types of SS welded together[19] (for the base and tie wings) makes these brackets weaker due to the heat generated from the welding procedure and possibly made the bracket more prone to elastic and plastic deformation than a metal injected molded bracket, such as a Damon Q bracket, that are constructed as one distinct piece of metal.

SS ligature ties effectively increases the stiffness of both types of brackets. In fact, SS plays a role in significantly ($p < 0.012$) limiting both types of elastic and plastic changes of slot width for both TS over TC and DS over DC (see Tables 4.4 and 4.5, respectively). Moreover, if a comparison between the two types of brackets is done, the twin brackets with steel ligation (TS) show superior behaviour over conventional Damon Q brackets (DC) in terms of significantly ($p < 0.012$) less deformation (less increase in slot width) from 0° up to 33° of the unloading angle of wire twist. After an angle of 30° on the unloading curve, TS and DC show no significant difference for about 15° then DC demonstrates significantly ($p<0.001$) less increase in slot width type of deformation than TS (Table 4.6). The range of bracket width changes varies depending on the type of the bracket and the ligation method. For example, the range witnessed for the Twin brackets with elastic ties was 29 μm (from 56μm at 45° to 27 μm at the end of experiment), which is a smaller range than that for Damon Q with no steel ties, 42 μm (from 49 μm to 7μm). A conclusion can be drawn from this that Damon Q brackets are stiffer than Orthos twin brackets and their geometry limits plastic deformation (Table 4.1). Moreover, when another comparison is done between the ranges of steel ligated groups to conventionally ligated brackets, it is obvious that SS ligature ties also reduced the range of deformation for both types of brackets.

For the first 6° there is a significant ($p < 0.012$) decrease in slot width for brackets ligated with SS ties (TS and DS). SS ties were able to elastically deform the brackets inwards then counter that by torquing the wire more to reach the plastic deformation point. Although this decrease in slot width may not be significant in a clinical setting, it does demonstrate that bracket slot width can be reduced *via* SS ligation. In this experiment, the wire was passively positioned at the time of ligation, whereas in a clinical scenario will only get this effect if the archwire is held in a passive position during wire ligation. However, if the wire is inserted at an angle and already actively engaged into the bracket slot wall then a reduction in slot width *via* wire ligation may not occur.

Nevertheless, this type of deformation was statistically significant, though the magnitude was less than 0.7 μm and the clinical relevance is questionable.

In a clinical application, as orthodontic treatment proceeds there are many forces and moments applied to the tie wings of a bracket during leveling, aligning, and sliding mechanics. These repeated stress applications could cause some deformation to the bracket as well as some increases in hardness of the brackets due to the work hardening of the bracket, possibly up to a 5–10% increase[21]. The application of steel ties would reduce the magnitude of deformation but, clinically, to what extent of a reduction takes place is difficult to estimate due to the previously described work hardening of the bracket. Moreover, the effects of steel ligation on reducing the amount of deformation would vary depending on the difference in design and material of the brackets.

Damon Q brackets ligated with steel ties (DS) had significantly ($p < 0.001$) less deformation (increase in slot width) than conventional Damon Q brackets (DC) at all angles, which would lead us to believe that DS should have higher torque than DC. However, that is not the case, as it has been presented before in Chapter 3 (DC had higher torque for the last 24°). If torque was not increased despite the reduction in the magnitude of deformation then there should be either an increase in the amount of wire indentation into the slot walls or increase in wire deformation. From the evaluation of the profile image data not much of difference in terms of wire indentation (notching) can be seen between DC and DS, which arguably leaving us to believe that more of wire deformation has occurred in the DS group.

In this research, wire deformation effects have not been considered, which will be the focus of future studies.

The error in this study can be divided into instrumental errors and other related to the methodology of the study. The automation of the testing procedures have significantly reduce the chance of human error. The measurement resolution of the overhead images is related to the accuracy of the image correlation process which was reported before by Lacoursiere et al[15] and it is as small as 0.15μm. The measurement error for the distance of the point of load application is related to the reliability of this testing procedure. One operator conducted all measurements and intra-rater reliability test was done and showed high reliability (ICC was about 90%). The methodology errors are related to a possible some variation in the force of the steel ligation, however this variation can resemble clinical situation where the force of the steel ligation is not measured. The manufacture tolerance of slot dimension and any possible deformation in the epoxy adhesive could contribute to potential variability and source of error.

4.5 Conclusion

The following conclusions can be stated:

1- Stainless steel ties reduce the amount of plastic deformation of both Orthos twin and Damon Q brackets.

2- A decrease in the slot width can be evident when stainless steel ligature is applied to a bracket. As steel ligation deformed the brackets inwards first, requiring more torque to lead them to plastically deform because the wire must first counteract this initial inwards deformation.

3- The position at which the wire engages into the slot wall is closer to the base of the slot for steel ligated brackets in comparison to conventionally ligated brackets.

4- Damon Q brackets show less plastic deformation than Orthos twin brackets ligated with elastic ties. However, Orthos twin brackets ligated with steel ties show no overall significant difference compared to the conventionally ligated Damon Q brackets.

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Chapter Five

General Discussion and Conclusions

5.1 General discussion

There are several variables that can affect the torque of a bracket, with one of them being the method of ligation. After a literature review on the ability of stainless steel (SS) ligation to provide greater torque on a bracket, it became clear that there was insufficient evidence to provide a definitive conclusion. Prior published research on ligation and its effect on torque failed to provide conclusive evidence, and indeed only contributed limited discussion, with regards SS ligation. SS ligation was suggested as a way of improving the torque of a bracket and of reducing bracket/wire slop; however, this idea was simply anecdotal. In fact, to date, no research has been published that primarily deals with the effects of SS ligature ties on the torque and deformation of brackets. Therefore, our research presented herein delivers some clarity to this matter and sheds some light on potential future research related to this subject.

The design of our apparatus meant that the values of torque generated in our experiment are higher than would be the case clinically; therefore, the focus of the discussion on the behaviour of the bracket rather than on the actual values of the moments. Despite the inherent limitation of a laboratory study, it was clear from our data that SS ligation made a difference in torque for Orthos twin brackets but that it did not make a clinical significant difference for Damon Q brackets. There was higher torque expressed for twin brackets that are ligated with SS ties compared to twin brackets ligated with elastic ties. SS ligation forced the wire into the slot of the bracket and created four leverage points (three with slot walls and one with the steel ligation) that made a difference in terms of torque compared to when two leverage points are created, as in conventionally-ligated brackets. The force of SS ligatures may vary depending on how tight it has been placed on the bracket, which also depends on the clinician's experience.

Nevertheless, one of the main effects of SS ligation that a clinician should pay attention to is the fact that a more immediate torque was detected and steel ligation reduced the engagement angle for both Orthos twin and Damon Q brackets. Depending on the bracket of use, this reduction may vary. For example, by using titanium brackets that are less stiff than SS brackets, the reduction of the engagement angle can be expected more significant[1]. Clinically this reduction is only possible if the archwire is held in a passive position during wire ligation. However, if the wire were inserted not in a passive position, the effects of SS ligation would be primarily a reduction in the deformation (less increase in slot width) of the bracket.

There are two types of deformation noticed after the torque experiment, one was related to the wire indentation into the slot walls (notching), and the other related to an increase in the slot width of the bracket. Bracket notching was more noticeable for Orthos twin brackets than for Damon Q brackets. SS ligation reduces the amount of bracket deformation (increase in slot width) for both types of brackets considered; however, this reduction of bracket deformation in certain incident (DS in the last 36° of unloading) was not adequate to sustain a significant difference in torque due to possible wire deformation interferences. As steel ties provide a physical support to the bracket and significantly reduce the amount of slot width increase type of deformation. There should be as consequences an increase in torque of the bracket, but if there were no increase in torque (DS in the last 36° of unloading) this means that there would be either increase in the depth of the notching in the bracket slot or increase in the wire deformation. Damon Q brackets showed relatively minor differences in notching which would lead us to believe that there was more of wire deformation with DS group in comparison to DC group.

Steel ligation contributes to the decrease in bracket deformation (slot width increase) in two ways: the first was by shortening the distance from the base of the bracket to the point where the edge of the wire engages the tie wing (shorter lever arm), and the second way was by providing a physical support to the bracket tie wings. However, It is not clear to what extent each of these described two ways contributes to the decrease in this type of deformation (slot width increase).

The properties and design of the brackets also played a prominent role in the torque and deformation magnitude of the brackets considered in our experiment. SS ties can improve the performance of inadequately designed brackets, especially in clinical situations where brackets endure significant amounts of force and moments throughout the course of treatment.

5.2 Strengths of the present study

This research followed previous work which resulted in refinement of equipment and methodology. The apparatus was able to measure torque expression, with high-resolution images to measure bracket deformation. No other torquing apparatus described in the literature is capable of providing such a combination of data. The multi-axis torque transducer that is capable of measuring forces and moments in three levels of space gives a unique feature to our apparatus that is not commonly used by, or available to, other researchers.

There are many differences between bench studies and clinical settings; however, the sample that chosen was large enough to control some of the errors, such as the variation in size of the bracket slot or wires. One operator conducting all of the tests reduced the amount of error in terms of the different forces of ligation and also made the steps of the experiment more consistent.

This research was performed with collaboration between Orthodontic and Mechanical Engineering Departments. The expertise and knowledge that were put into this technical research added extra value and gave a deeper understanding of the subject matter, thereby making for a well-rounded research project.

5.3 Limitations of the study

5.3.1 Limitation of findings

It is clear that our findings are specific to a certain size and material of wire/bracket combination. Rock and Wilson[2] noted, as far back as 1989, that the role of wire material and its size can be a significant factor on the forces exerted by the wire with different ligations. More recently, Hirai et al.[3] reported that a full-dimension archwire (0.021 × 0.028 inches in a 0.022-inch slot) makes no difference in terms of ligation method. Therefore, the significance of the effects of SS ties should be considered with the relative bracket/wire relationship used in this research.

5.3.2 Clinical limitations

The absence of play angle in the adjacent brackets has affected the calculated values of torque generated in our experiment. Furthermore, the absence of periodontal ligament in all *in vitro* studies means that, from a clinical point of view, there is a significant limitation placed upon the interpretation of the experimental findings.

5.3.3 Mechanical limitations

Placing stainless steel ties on the brackets was challenging due to the limited space and access available after positioning the bracket in the apparatus. Moreover, calculating the force of ligation was not done. Damon Q brackets are not meant to be steel ligated, with their bracket design having an inherently low profile, which therefore made it a challenge to place a steel ligation.

Measurement error of the load cell used in our experiment was previously reported to be 1.5 %[4]. No further calibration of the device was carried out to make allowances for any modifications that were made. Further, mounting brackets on the bracket holders with a different thickness of glue could introduce some small measurement errors that were not accounted for in our experiment.

5.4 Recommendations for future studies

Measuring wire deformation is potentially just as valuable as it is for bracket deformation. Clinically, the different bends brought about the wire during the finishing stage of treatment cause significant deformation to the wire, that combined with any deformation to the wire resulting from the chewing process, will almost certainly affect the physical properties of the wire and consequently the ability to provide a proper torque expression.

Measuring wire deformation is not straightforward, especially if clinical variables are taken into consideration. Major et al[5] and Meling et al[6] have tried in the past to measure wire deformation in a laboratory setting; however, even under such an environment, controlling all of the variables to achieve accurate measurements caused some challenges. Therefore, as part of our efforts of continued research, a plan on using the same novel approach to this study, but of twice measuring the torque angle then subtracting the bracket deformation to give a reading for the wire deformation that is as accurate as is currently possible.

Clinically, when torque is applied to a bracket, the tooth's response can vary and, in many cases, a second application of torque is required. Repeated torque on a bracket is also an important aspect that should be evaluated by future research in order to determine whether there is any additive effect upon bracket deformation.

Although orthodontists level and align teeth before torque is applied to a bracket, in many cases, at the end of tooth movement, there will be a small second-order moment (mesial-distal direction) left at the tooth that is less than the threshold to generate tooth movement. These second-order moments can affect the torque of a bracket[7]. Therefore, of interest to us is future research to assess the effects of second-order moments on torque and bracket deformation.

Applying SS ties to different types of bracket and designs may provide different findings. For instance, applying SS ties to titanium brackets may have more significant effects in terms of torque compared to SS brackets, due to the increased elastic nature of titanium over stainless steel[1]. Future research to study the effects of SS ties on different types of brackets is an avenue worthy of pursuit.

5.5 Conclusions

In this research, it has been provided a novel means of measuring and evaluating the torque and bracket deformation both with, and without, stainless steel (SS) ligature ties on conventional and self-ligated brackets. Our findings show that steel ligatures increase the amount of torque that are generated by conventional twin brackets compared to self-ligated Damon Q brackets. Moreover, SS ligature ties reduction of the plastic bracket deformation was related to limiting the increase in slot width for both types of brackets.

5.6. Bibliography

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Appendix

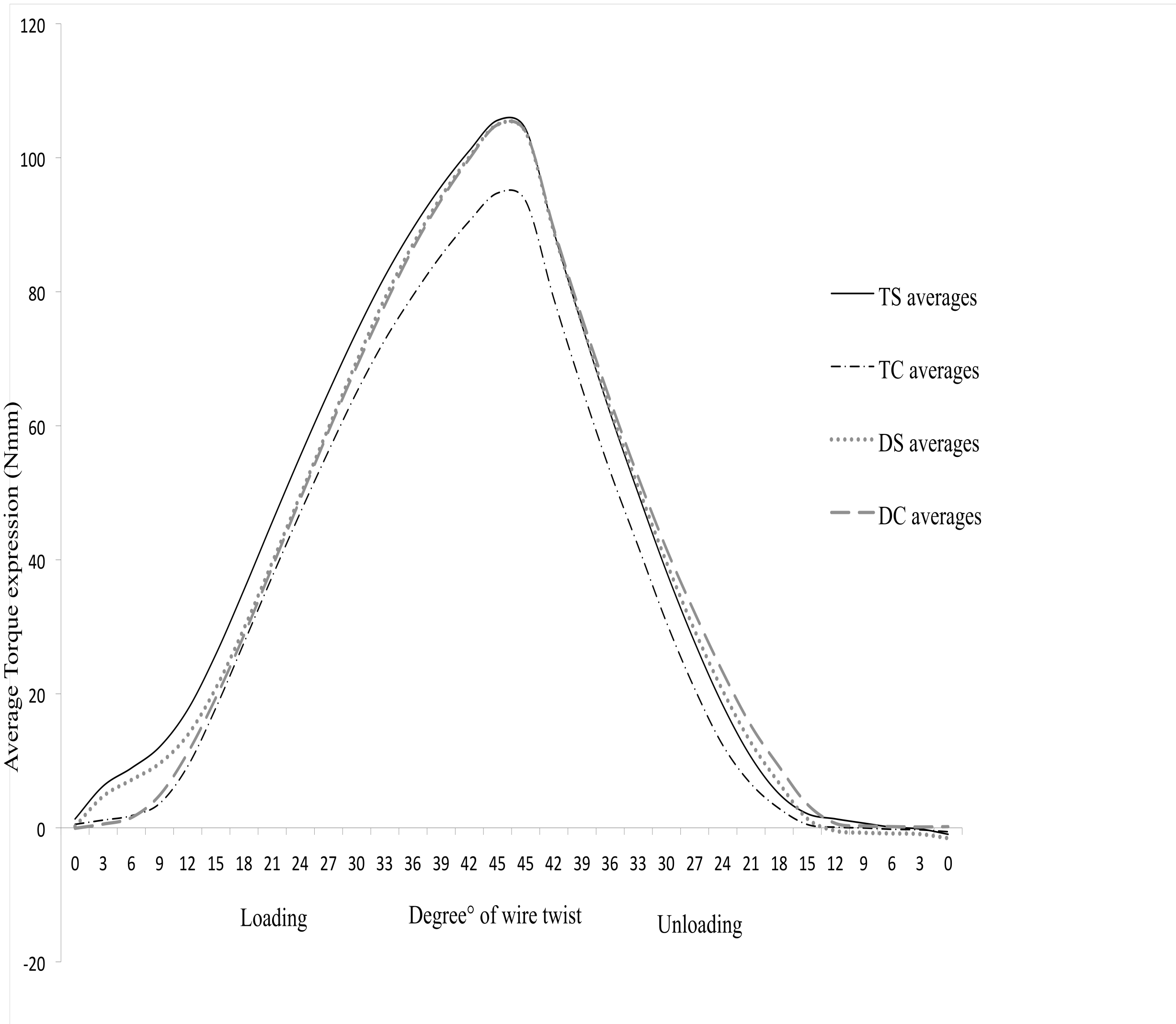

Figure A: Average torque (Nmm) with respect to twist angle (degrees) for loading and unloading of all groups (TS: Orthos twin bracket with steel tie, TC: Orthos twin bracket with conventional tie, DS: Damon Q with steel tie, and DC: Damon Q with the conventional sliding door).