University of Alberta

The Effect of Conventional Elastomers on Force and Moment of a Self-Ligating Orthodontic Bracket with Second-Order Angulation in the Dry and Wet States evaluated through a new 3D Friction Device

by

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A thesis submitted to the Faculty of Graduate Studies and Research
in partial fulfillment of the requirements for the degree of

Master of Science
in
Medical Sciences - Orthodontics

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Spring 2013
Edmonton, Alberta

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Dedication

For Mom, Dad, Kamran, and Kayvan

I love you all

Abstract

Objective: A new three-dimensional friction device was used to investigate the effect of conventional elastomers on force and moment of a self-ligating orthodontic bracket with second-order angulation during a simulated retraction.

Methods: An 0.018x0.025-in stainless steel archwire was drawn through a 0.022-in Damon Q self-ligating bracket at a rate of 6mm/min. 130 brackets, 65 with and 65 without conventional elastomers, were tested at angulations from 0° to 5° and in dry and wet (human saliva) states. Force and moment values were recorded in x, y, and z directions.

Results: There was strong evidence for force and moment to be significantly influenced by the effects of angulation, elastomer, state, and all interactions. Angulation, elastomer, and the interaction of angulation and elastomer were the primary influencers, whereas saliva had little effect or lubricious behavior.

Conclusions: The tested self-ligating bracket had less force and moment compared to the same bracket with elastomer addition.

Acknowledgement

Dr. Paul Major, Dentistry

Dr. Roger Toogood, Mechanical Engineering

Dr. Giseon Heo, Dentistry

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List of Symbols and Abbreviations used in Tables

A-NiTi, Austenitic Nickel-Titanium.

BI, Binding.

C, Canine.

CB, Conventional Bracket.

CE, Ceramic.

CEL, Conventional Elastomeric Ligature.

CI, Central Incisor.

CoCr, Cobalt Chromium.

CPTi, Commercially Pure Titanium.

CS, Crosshead Speed.

CuNiTi, Copper Nickel-Titanium.

DR, Demineralization/Remineralization Regimen.

FR, Friction.

Grp, Group.

KF, Kinetic Friction.

LI, Lateral Incisor.

MC, Metal-reinforced Ceramic.

MCA, Molycrystalline Alumina.

M-NiTi, Martensitic Nickel-Titanium.

N/A, Not Applicable.

NCEL, Nonconventional Elastomeric Ligatures.

NiTi, Nickel-Titanium.

PC, Polycarbonate.

PCA, Polycrystalline Alumina.

PM, Premolar.

PO, Porcelain.

RS, Resistance to Sliding.

SA, Sapphire.

SF, Static Friction.

SL, Self-Ligating.

SLB, Self-Ligating Bracket.

SS, Stainless Steel.

SSL, Stainless-Steel Ligature.

TCL, Teflon-Coated Ligature.

Ti, Titanium.

TMA, Titanium Molybdenum Alloy.

θ, Angulation of bracket-wire interface.

θ_C, Critical contact angle of binding.

Chapter 1. Introduction and Literature Review

1.1 Statement of the Problem

Friction in the bracket-archwire interaction is of great interest in orthodontic sliding mechanics. Current in-vitro experiments pull a wire through a bracket slot or slide a bracket along a fixed wire[1,2] and record one-dimensional (1D) frictional data at the wire level. No three-dimensional (3D) model measuring force and moment at the bracket level has been published, although intuitively an understanding of force and moment in 3D space is essential[3] to effectively analyze tooth movements.

1.2 Introduction

A general overview of friction and resistance to sliding will be presented, followed by the significance of the study, research aims, and hypotheses.

1.2.1 Friction

Friction is notably a complex phenomenon where a dynamic series of interactions take place.[4] Friction is defined as a force that resists movement as one surface slides relative to another[5] and acts in the opposite direction of movement[6]. Mathematically, friction force is the product of the normal force and the coefficient of friction[7] only when objects are approaching motion or during sliding. The normal force acts perpendicular to the surface of an object,[7] whereas the coefficient of friction is a constant that varies by the materials surface characteristics,[7,8] including surface roughness, texture, and hardness[2]. Notably, a moment is defined as a rotational potential of a force with respect to a specific axis or point.[3] The key to controlling friction includes maximizing efficiency, the resultant force compared to the applied force, as well as reproducibility, the ability to behave predictably when certain mechanics are employed.[4]

The laws of friction and physiology apply to orthodontic tooth movement.[1] Tooth movement is not a smooth continuous motion, but rather a series of short steps.[1,9] In orthodontics, friction is a consequence of any sliding mechanics,[4,10] such as during alignment, leveling, and space closure[11]. Low friction facilitates efficient arch leveling and alignment[12] and space closure while maintaining low anchorage requirements[13]. However, high friction is desirable in some clinical situations when expressing torque in the bracket or during the finishing and detailing stage of treatment.[12] To generalize, the goal is for minimal or ideally nil frictional forces.[10] For a desired path of tooth movement, the force applied must conquer friction whilst maintaining light optimal forces.[14]

During tooth movement, the two types of friction are designated as static friction, the resistance that prevents initial movement, subsequently replaced by kinetic friction, which acts during the period of motion.[5,9] Static and kinetic friction continuously alternate in orthodontic movement as a tooth intermittently slides and binds along the archwire.[11] It is debatable which form to measure, as both are applicable in clinical situations. Although authors have evaluated either static or kinetic friction or even combined them, it is commonly not clear which measurement was recorded or which was most relevant.[15]

1.2.2 Resistance to Sliding

In sliding mechanics, resistance to sliding (RS) equates to the additive effect of friction (FR), binding (BI), and notching (NO), where FR is partitioned into plowing (PL), roughness interlocking (IN), and shearing (SH) components.[4,16,17] In other words, friction is one component of total resistance. Plowing occurs when one material is much harder than the other; interlocking occurs when asperities of one surface engage the other surface; and shearing occurs when asperities break off and attach to one surface or fall into interspace.[4] Binding occurs once the wire simultaneously contacts diagonal tie-wings of a bracket.[17] Notching, the ultimate manifestation of binding, is when plastic deformation has occurred at the diagonal tie-wings or opposing wire contacts, resulting in ceased sliding motion.[17] The overall expression of RS is[4]:

$$RS = (FR) + BI + NO = (PL + IN + SH) + BI + NO.$$

Angulation of the bracket-wire interface (θ) and critical contact angle (θ_c) distinguishes whether friction or binding dominates in the expression for RS.[16] Friction and binding magnitudes are important for efficient and effective management of sliding mechanics.[17] RS can be categorized into four specific stages[4,16]:

1. When $\theta < \theta_c$, RS = FR.
2. When $\theta \geq \theta_c$, RS = FR + BI.
3. When $\theta > \theta_c$ and BI >> FR, RS ≈ BI.
4. When $\theta >> \theta_c$ and NO >> BI >> FR, RS ≈ NO ≈ ∞ (i.e. sliding is unachievable).

As angulation increases the role of binding increases, with the consequence of more difficult sliding mechanics above θ_c.[16,17] Therefore, maintaining the angulation near θ_c is critical to enhanced sliding mechanics. With quantities of archwire width (size), slot width (slot), and bracket width (width), the theoretical equation for θ_c (°) is approximately[16]:

$$\theta_c = \frac{57.32[1 - \left(\frac{size}{slot}\right)]}{\left(\frac{width}{slot}\right)}.$$

Friction and binding phenomena exist in sliding mechanics to close or regain space. Clinical studies support experimental findings that resistance to sliding is mostly due to binding, which is intermittently released by oral function.[18] By controlling resistance to sliding, more efficient and reproducible fixed orthodontic appliances can prevail, thereby enhancing treatment and not extending overall treatment time.[7]

Misperception accelerates when studies reporting friction are in fact evaluating resistance to sliding[19] or less commonly the converse of reporting resistance to sliding when evaluating friction. Some studies do not provide clear definitions of measurement outcomes and utilize the term friction loosely. As the topic of resistance to sliding is complex, authors believe the term friction facilitates reading and understanding, although terms are not interchangeable.[19] Friction has become a popular marketing topic among orthodontic suppliers, where manufacturers and clinicians incorrectly generalize this term resulting in a continued escalation of misunderstanding. Education of resistance to sliding to practitioners is paramount to eliminate misuse of terms in clinical practice and in published literature. Additionally, only Robert Kusy and his colleagues have identified binding in the literature, whereas other authors simply used the term friction. Importantly, binding is a friction phenomenon, although the underlying physical mechanism of friction and binding are certainly different.

1.3 Significance of the Study

The nature of ligation and angulation of the bracket-wire interface can significantly influence friction[9,20] and binding, where increases in ligation force[9] or angulation[11] enhance resistance to sliding. Experimental testing in dry and wet environments is beneficial to simulate intra-oral conditions. The effect of conventional elastomers on force and moment of a self-ligating bracket with angulation in the dry and wet states evaluated through a new 3D device will be studied.

1.4 Research Aims

The aims of this research study were to:

1. Utilize a novel 3D device to evaluate resistance to sliding during canine retraction on a continuous archwire.
2. To compare the 3D results with past research.
3. To evaluate the main effects of elastomer ligation, state, angulation, and interactions by studying the result of conventional elastomeric ligation on the force and moment of a self-ligating bracket with angulation in the dry and wet states.
4. To determine the dominant influences on force and moment and to quantify amount.
5. To calculate the coefficient of kinetic friction and compare to literature.

1.5 Hypotheses

The null hypotheses of interest were namely:

H_0: Mean force and moment are the same for elastomeric and no elastomeric ligation.

H_0: Mean force and moment are the same for dry and wet state.

H_0: Mean force and moment are the same for 0° and 5° angulation.

H_0: At 0° and 5° angulation, there is no difference in mean force and moment between elastomeric and no elastomeric ligation.

H_0: At 0° and 5° angulation, there is no difference in mean force and moment between dry and wet state.

With reference to Robert Kusy's work, further hypotheses of interest included:

H: An experimental distinction of θ_c exists, where friction dominates below θ_c and binding dominates above θ_c.

H: The experimental θ_c value agrees with the theoretical θ_c equation based on bracket and wire geometry.

H: Above θ_c, resistance to sliding increases linearly with angulation.

H: Elastomeric ligation superimposes a constant offset of the resistance to sliding to angulation curve.

1.6 Literature Review

An overview of conventional and self-ligating brackets will be discussed. For the purpose of my research, a current literature review was completed for conventional elastomeric ligature, state, and angulation separately, as well as factors combined, followed by a summary of experimental methodologies.

1.6.1 Conventional and Self-Ligating Brackets

As technology continues to evolve, manufacturers are developing new products at a rapid pace to stay competitive while introducing design modifications to decrease resistance to sliding.[21] Clinicians continue to have the luxury of choosing specific bracket design, prescription, material, in addition to wire sizes and materials. Conventional brackets need a form of ligation to hold the archwire into the bracket slot. With popularity on the rise, self-ligating bracket have a movable fourth wall that converts the bracket slot into a tube in order to engage the archwire. An active self-ligating bracket has a clip that presses against the archwire, whereas a passive self-ligating bracket does not.

Debates about the frictional properties of conventional bracket versus self-ligating bracket and active versus passive self-ligating bracket are heavily evaluated, although little consensus exists in the literature. Burrow[18] confirmed that resistance to sliding was a binding-and-release phenomenon relative to friction and was determined similar for conventional bracket and self-ligating bracket. However, passive and active self-ligating brackets were found to have less static and kinetic friction compared with conventional brackets.[22] A recent systematic review of 19 papers concluded that self-ligating bracket produced less friction compared with conventional bracket with small round archwires in the absence of tipping and/or torque in an aligned arch.[19] This review further concluded there was a lack of evidence for self-ligating bracket producing lower friction than conventional bracket with large rectangular wires in the presence of tipping and/or torque in arches not-aligned.[19] Furthermore, passive self-ligating bracket had lower static and kinetic friction than active self-ligating bracket,[12] although the converse finding of no significant difference in frictional force between passive or active self-ligating bracket also existed[22]. The high variability in experimental designs and little uniformity in methodology may account for some inconsistencies. With no standardized protocol for testing resistance to sliding, each research team develops its own apparatus.[23]

A vast number of experiments exploring factors that influence friction and binding for sliding mechanics have studied bracket width, inter-bracket distance, archwire material and size, ligation method, state, and angulation, among a list of others. Specifically, conventional elastomeric ligature, state, and angulation were reviewed in this paper.

1.6.2 Conventional Elastomeric Ligature

The ideal properties of ligation include being secure, robust, quick, and easy to use, ensuring full engagement of the archwire, exhibiting low or when desirable high friction, allowing easy attachment of elastic chain, assisting good oral hygiene, and being comfortable for the patient.[24] Although the mainstream ligation types include conventional elastomeric ligatures (CEL) and self-ligating brackets, nonconventional elastomeric ligatures (NCEL) and stainless-steel ligatures (SSL) are also utilized.

Convenience, speed, and ease of application ensures clinician popularity with CEL,[14] as well as patient comfort and satisfaction with an array of colors, relatively hygienic, and inexpensive.[25,26] CEL disadvantages include incomplete seating of the wire, greater bacterial attraction,[26] and permanent deformation and hydrolysis over time since they are made of polyurethane-based polymer.[14,25,26] The consequences include high decay rates of elastomeric forces,[25] which alter the degree of friction[14] and warrant frequent elastomeric changes[22]. NCEL include modifications of CEL properties, such as special coatings or angled elastomers. Although SSL are commonly used, their time-consuming nature is the largest drawback for clinicians. Self-ligating brackets have overcome limitations of CEL and SSL, including ergonomics, efficiency, deformation, discoloration, plaque control, and debatably friction.[13] Without supporting evidence self-ligating bracket claims include more secure archwire engagement, reduced friction, improved chair-side efficiency, less chair-side assistance,[24] fewer appointments, and overall reduction of treatment time[27]. However, a review article concluded that the evidence from clinical studies of reduced treatment time with self-ligating bracket does not exist.[18] Interestingly, some practitioners apply CEL over self-ligating bracket, due to a patient's request for colors, thereby transforming the self-ligating bracket to a conventional bracket.

The nature of ligation significantly influences friction,[20] specifically, increases in ligation force enhance frictional resistance[9]. With ligation as the lone study variable, a compilation of published research investigating friction of CEL with any other form of ligation (Table 1-1) illustrated conflicting conclusions. Generally, CEL exhibited more friction than other ligation forms, although some studies determined the opposite or no difference in friction between ligation methods. Overall, no consistent pattern existed for the frictional forces of conventional elastomers. Study limitations included small sample size, confounding variables of elastomers, brackets, and wires, lacking a standardized technique for CEL pre-stretching and placement, no standardized SSL technique, testing at 0° angulation and only one state (dry or wet), and unknown variables of frictional measurement, sample size, and bracket number. Future studies should address these limitations to make sound conclusions regarding elastomer ligation and resistance to sliding.

Table 1-1. Research papers investigating friction of conventional elastomeric ligature with any other form of ligation (n=16).

Author	Friction Type (s)	Bracket (s)	Wires (inch)	Ligation Method (s)	Conclusions	Limitations
Arun & Vaz 2011 [25]	Frictional Resistance	1 SS CB *	0.019x0.025 SS	4 CEL NCEL (Coated) NCEL (Angled)	-NCEL (Angled) significantly < FR followed by NCEL (Coated) -No difference FR with different ligature diameters	-Small sample size: 5 tests total -Different elastomers tested within one test group -Tested θ = 0° -Dry state only
Baccetti & Franchi 2006 [28]	SF KF	1 SS CB *	0.014 NiTi 0.019x0.025 SS	CEL NCEL (Slide)	-NCEL (Slide) significantly < SF and KF than CEL for aligned and misaligned brackets	-Brackets re-used for testing -Tested θ = 0° -Dry state only -No ligature gun utilized
Bednar et al 1991 [20]	FR	1 SS SLB 1 SS CB 1 CE CB	0.014 SS 0.016 SS 0.018 SS 0.016x0.016 SS 0.016x0.022 SS	SLB CEL Lightly SSL	-Lightly SSL had < FR than CEL	-Small sample size -Same brackets and wires used for repeated tests -Tested θ = 0° -Dry state only -No ligature gun utilized
Chimenti et al 2005 [14]	SF	1 SS CB *	0.019x0.025 SS	3 CEL 2 NCEL (Coated)	-Small and medium CEL significantly < SF than large CEL (13-17% decrease SF) -NCEL (Coated) significantly < SF than CEL (23-43% decrease SF)	-Small sample size -Tested θ = 0° -Dry state only -No ligature gun utilized
Cordasco et al 2009 [29]	KF	1 SS SLB *	0.014 CuNiTi	SLB SLB + CEL SLB + SSL	-Passive SLB significantly < FR than CEL or SSL -No significant difference FR when comparing CEL and SSL	-3 bracket model had same bracket number, bracket number not reported -High standard deviation SSL, no standardization SSL placement

						-Tested θ = 0° -Dry state only -No ligature gun utilized
Franchi et al 2008 [30]	SF KF	4 SS SLB 1 SS CB *	0.019x0.025 SS	SLB CEL NCEL (Slide)	-SLB and NCEL significantly < frictional forces (<2g) than CEL (>500g)	-Tested θ = 0° -Dry state only -No ligature gun utilized
Gandini et al 2008 [31]	SF KF	1 SS SLB 1 SS CB	0.014 NiTi 0.019x0.025 SS	SLB CEL NCEL (Slide)	-NCEL (Slide) significantly < FR than CEL	-Small sample size -Unknown bracket number for central incisor -Repeated use of brackets and wires -Tested θ = 0° -Dry state only -No ligature gun utilized
Khambay et al 2005 [32]	Unknown	1 SS CB	0.019x0.025 SS 0.017x0.025 SS Note: Both wires U shaped	3 CEL NCEL (Coated) SSL	-SSL < mean frictional forces, whereas CEL grey produced significantly > mean frictional force -Seating force of wire into bracket not related to subsequent mean frictional force produced	-Small sample size -Unknown bracket number for premolar -Unknown friction type -Tested θ = 0° -Wet (human saliva) state only
Khambay et al 2004 [10]	Frictional Resistance	1 SS CB	0.017x0.025 SS 0.017x0.025 TMA 0.019x0.025 SS 0.019x0.025 TMA	2 CEL NCEL (Coated) NCEL (Angled) SSL	-CEL purple lowest FR for 0.017x0.025 TMA -SSL lowest frictional force for all other wires -No consistent pattern in frictional force	-Unknown bracket number for premolar -Tested θ = 0° -Wet state (human saliva) only -Unknown sample size for validation study -SLB conclusions, but no SLB in main study
Krishnan et al 2009 [22]	SF KF	4 SS SLB 1 SS CB	0.019x0.025 NiTi 0.019x0.025 SS 0.019x0.025 TMA	SLB CEL	-Passive and active SLB < SF and KF compared with CB -With passive or active SLB, SS wire did not produce significant difference in frictional force	-Unknown bracket number for canine -Tested θ = 0° -Dry state only -No ligature gun utilized

Matarese et al 2008 [8]	KF	1 SS SLB 1 SS CB *	0.014 NiTi 0.016 NiTi 0.016x0.022 NiTi 0.0155 coaxial SS 0.016 SS 0.016 TMA	SLB CEL SSL	-No significant difference between CEL and SSL (n=10)	-Small sample size -Unknown bracket number for premolars and canine -High standard deviation SSL -Author: large inter-bracket distance -Tested θ = 0° -Dry state only -No ligature gun utilized
Sims et al 1993 [33]	KF	2 SS SLB 1 SS CB	0.016x0.022 SS 0.017x0.025 SS 0.018x0.025 SS 0.019x0.025 SS	SLB 2 CEL	-CEL figure 8 significantly > FR by a factor of 70-220% compared to CEL, except for 0.016x0.022 inch wire	-Small sample size -Tested θ = 0° -Dry state only -No ligature gun utilized
Sirisaowaluk et al 2006 [6]	SF	1 SS CB *	0.016x0.022 SS	3 CEL NCEL (Coated) SSL TCL 2 Twist Ligature	-Repeated vertical displacement < FR, except CEL figure 8 -SSL figure 8 < FR, CEL figure 8 > FR -Both Twist Ligatures least FR -Significant differences: CEL > FR SSL/TCL, TCL > FR SSL, NCEL (Coated) and TCL < FR CEL -No significant differences: NCEL (Coated) and TCL, CEL 2 corners and SSL	-Unknown bracket numbers for 3 lower incisor model -Author: clinically low load for vertical displacement -Tested θ = 0° -Dry state only -No ligature gun utilized, CEL pre-stretched 24hr
Taylor & Ison 1996 [15]	SF KF	2 SS SLB 1 SS CB *	0.018 SS 0.020 SS 0.016x0.022 SS 0.018x0.025 SS 0.019x0.025 SS	SLB CEL SSL Loose SSL Note: No module or pre-stretched CEL for some tests.	-FR increased as number of brackets increased -Ratio SF to KF consistent For 0.018 SS: -SSL significantly < FR than CEL -Pre-stretched CEL or loose SSL significantly < FR than CEL or SSL	-Unknown sample size -No standardized technique for SSL, pre-stretching CEL, or ligature gun -Tested θ = 0° -Dry state only

Tecco et al 2009 [34]	FR	1 SS CB *	0.014 NiTi 0.016 NiTi 0.018 SS 0.016x0.022 NiTi 0.016x0.022 SS 0.017x0.025 NiTi 0.017x0.025 SS 0.017x0.025 TMA 0.019x0.025 NiTi 0.019x0.025 SS	CEL 3 NCEL (Slide)	-NCEL (Slide) significantly < FR than CEL with round wires only, not rectangular archwires -Different NCEL (Slide) sizes do not cause differences in FR	-Small sample size -10 aligned brackets in model had same bracket number -Repeated use of brackets -Tested θ = 0° -Dry state only
Tecco et al 2007 [35]	FR	2 SS SLB 1 SS CB *	0.016 NiTi 0.016x0.022 NiTi 0.017x0.025 TMA 0.019x0.025 NiTi 0.019x0.025 SS	SLB CEL NCEL (Slide)	-NCEL (Slide) had < FR than CEL for all wires	-10 aligned brackets in model had same bracket number & bracket number unknown -Repeated use of brackets -Tested θ = 0° -Dry state only -No ligature gun utilized

* = Segment of brackets tested (i.e. more than 1 bracket)

1.6.3 State

Experimental conditions may involve a dry and/or wet state, where wet refers to artificial or human saliva. Both dry and wet states occur in the oral cavity. Specifically, dry surfaces contact when the archwire and bracket force out the layer of saliva and wet surfaces are sourced from the patient's salivary glands.[4] With state as the lone study variable, a compilation of published research investigating friction of at least two states (Table 1-2) displayed contrasting results. Generally, saliva was found to exhibit either adhesive or lubricious behaviors on frictional force. One study concluded that artificial saliva was not an ideal alternative to human saliva for in-vitro frictional testing.[36] The prevailing limitations were small sample size, confounding variables of operators, brackets, and wires, lacking standardized techniques for CEL and SSL placement, as well as saliva application, testing at 0° angulation, and unknown bracket number. Future experiments should ideally eliminate these limitations to determine the true effect of saliva on resistance to sliding.

Table 1-2. Research papers investigating friction of at least two states (n=3).

Author	Friction Type (s)	Bracket (s)	Wires (inch)	State (s)	Conclusions	Limitations
Al-Mansouri et al 2011 [36]	SF	1 SS CB	0.019x0.025 SS	1) Dry state 2) Artificial saliva pre-soaked 24hr 3) Human saliva pre-soaked 24hr	-Differences in SF between 3 lubricants approached statistical significance (p=0.059) -Difference between artificial saliva and human saliva weak statistical significance, but human saliva and dry state similar SF -Artificial saliva not an ideal alternative to human saliva for friction testing in laboratory	-Applied lubricant with soft brush, non-standardized amount -Tested θ = 0° -No ligature gun utilized for CEL
Downing et al 1995 [23]	SF KF	1 SS CB 1 CE CB	0.018 NiTi 0.018 SS 0.018 TMA 0.019x0.025 NiTi 0.019x0.025 SS 0.019x0.025 TMA	1) Dry state 2) Artificial saliva	-Artificial saliva increased frictional force when compared to dry state -Artificial saliva does not appear to act as a lubricant	-Unknown bracket number for central incisor -Unclear if repeated testing of same brackets and wires -Tested θ = 0° -No ligature gun utilized for elastomeric chain
Kusy et al 1991 [37]	SF KF	2 SS CB 2 PCA CB	0.018x0.025 NiTi^ 0.021x0.025 NiTi^ 0.018x0.025 CoCr 0.021x0.025 CoCr 0.018x0.025 SS 0.021x0.025 SS 0.018x0.025 TMA^ 0.021x0.025 TMA^ ^ = Preformed wires	1) Dry state 2) Human saliva	-The mixed reports that saliva may promote adhesive and lubricious behaviors may have some substance: couples with TMA wires exhibit lubricious behavior in wet vs. dry state, couples with SS wires suggest some adhesive behavior in the wet vs. dry state	-Small sample size -Unknown bracket number for premolar -Repeated testing of wires unknown -Used 2 SSL for ligation of each bracket and no standard technique for SSL placement -2 operators prepared and tested samples separately and used their own saliva, resulting in variability -Tested θ = 0°

1.6.4 Second-Order Angulation

As previously noted, θ is the second-order angulation of bracket-wire interface or as clinicians refer to, bracket tip. Frank and Nikolai[9] concluded angulation to be the most influential factor on frictional force, where increases in angulation increased frictional resistance.[11] Moore et al[1] also concurred that angulation was the most important determinant of friction in orthodontics. With angulation as the lone study variable, a compilation of published research investigating friction and binding of more than one angulation (Table 1-3) demonstrated similar findings. The consensus was for resistance to sliding to increase with angulation, where binding played a role. Although resistance to sliding significantly increased with angulation and torque separately and in combination, angulation was more influential.[2] The underlying limitations involved small sample size, confounding variables of elastomers, brackets, and wires, lacking standardized techniques for CEL and SSL placement, not reporting θ_c, testing in dry state only, and unknown bracket number. Experiments studying resistance to sliding above θ_c were limited as accurate angulation measurement was difficult.[16] Noteworthy, a review paper suggested incorporation of rectangular wires with angulation to make conclusions applicable for all stages of treatment.[19] Future studies excluding these limitations would strengthen the research quality of angulation and resistance to sliding.

Table 1-3. Research papers investigating friction and binding of more than one second-order angulation (n=7).

Author	Friction Type (s)	Bracket (s)	Wires (inch)	Angulation (s)	Conclusions	Limitations
Articolo & Kusy 1999 [7]	Kinetic RS	1 SS CB 1 PCA CB 1 MCA CB	0.021x0.025 NiTi 0.021x0.025 SS 0.021x0.025 TMA	0°, 3°, 7°, 11°, and 13°	-BI emerged when no bracket clearance remained -RS increased with θ -BI increased in importance with θ and was additive to FR component	-Small sample size: only 1 test each (different loading values) -Unknown bracket number -2 SSL used per bracket, no controlled ligation force -Dry state only
Dickson et al 1994 [38]	SF	1 SS CB	0.0155 coaxial SS 0.016 NiTi 0.016 SS 0.016 epoxy-coated SS 0.017 fibre-optic glass	0°, 5°, and 10°	-SF increased significantly with increased θ due to BI	-Small sample size -Unknown bracket number for central incisor -Ligation method: friction-free ligature force -θ_c not reported -Dry state only
Hamdan & Rock 2008 [2]	KF	1 SS CB	0.019x0.025 SS	0°, 4°, 8°, and 12°	-RS significantly > by θ and torque separately and in combination, although θ had more powerful influence than torque	-Unknown bracket number for premolar -Brackets and wires re-used -Dry state only -No ligature gun utilized
Moore et al 2004 [1]	SF KF	1 SS CB 1 CoCr CB	0.019x0.025 SS 0.021x0.025 SS	0°, 1°, 2°, and 3°	-Mean SF and KF very similar -Increased θ associated with highly significant increases in FR -FR doubled with every degree of θ	-Combined SF and KF for analysis -CEL changed every 10 tests -θ_c not reported -Dry state only -No ligature gun utilized
Pizzoni et al 1998 [39]	FR	2 SS SLB 2 SS CB	0.018 SS 0.018 TMA 0.017x0.025 SS 0.017x0.025 TMA	0°, 3°, 6°, 9°, and 12°	-FR increased with angulation -SLB significantly < FR than CB -SLB: passive significantly <	-Unknown bracket number for premolar -Only 2 tests for each -Correction factor for friction

					FR active	measuring device -Filter to average spikes in signal -θ_c not reported -Dry state only -No ligature gun utilized
Redlich et al 2003 [40]	SF KF	1 SS SLB 5 SS CB	0.018 SS 0.018x0.025 SS 0.019x0.025 SS	0°, 5°, and 10°	-FR increased as θ increased	-Focused on SF only; KF not considered as sliding of tooth not continuous or constant motion -θ_c not reported -Dry state only -No ligature gun utilized
Thorstenson & Kusy 2002 [41]	RS	4 SS SLB	0.014 A-NiTi 0.016x0.022 A-NiTi 0.019x0.025 A-NiTi 0.019x0.025 M-NiTi 0.019x0.025 SS	-9° to +9° Note: At increments of 1°	-When clearance disappears, RS increased proportionally with θ	-Small sample size -Unknown bracket number for premolar -Unclear if wires re-used for testing -Dry state only

1.6.5 Combined Conventional Elastomeric Ligature, State, and/or Second-Order Angulation

Researchers that investigated friction and binding from multiple factors of conventional elastomeric ligature, state, and/or angulation (Table 1-4) were in agreement with our previous conclusions. Half of the papers established CEL to have more friction than other ligation forms, whereas the other half of papers reported CEL to have less or no difference in friction between the ligation methods. This spectrum of results concurs with our earlier conclusion of no consistent pattern for the frictional forces of conventional elastomers.

Artificial and human saliva were not the only parameters of a wet state, as testing for some studies also occurred in a water bath or in-vivo. Wet states (Table 1-4) illustrated either adhesive behavior, lubricant property, or no effect on friction, which supported the previous inconsistent influence of saliva on friction. To summarize, a complex pattern was evident for saliva, where frictional forces could increase, decrease, or not change. As one expects for rough surfaces, lubrication significantly reduced friction.[11] Conversely, in other reported experiments, lubrication increased frictional forces, with the explanation that water and polar liquids, like saliva, increase adhesion or attraction of polar materials and therefore increase friction.[23] Therefore, the effect of saliva on friction was inconsistent from previous studies.[23] Kusy and Whitley[4] recognized the controversy over whether saliva acted as a lubricant or an adhesive during sliding mechanics and concluded that saliva could behave as either a lubricant or an adhesive depending on the bracket-archwire couple, specifically the materials physical and chemical characteristics. They further concluded that water and artificial saliva were not valid substitutes for clinical application.[4] With continued research, the generalized variation of saliva influence confirmed the inconsistency between dry and wet states.[55] Future saliva research investigating additional factors that may explain this inconsistency would be valuable, as the cause is unknown.

The literature continued to be in agreement for the effect of angulation, where friction and binding increased with angulation (Table 1-4). Furthermore, angulation had a significant effect under dry and wet states.[11] Moreover, with $\theta < \theta_c$ for both states, friction was independent of angulation, whereas, with $\theta > \theta_c$ for both states, resistance to sliding increased with angulation.[21] For the latter, a linear relationship was suggested between binding and angulation.[21]

These study limitations were comparable to limitations previously noted, except with additions of unequal sample size per group, confounding saliva variable, and unknown wire material and wet state composition (Table 1-4). Future studies warrant more controlled experimental methods to strengthen the research quality and thereby, research conclusions.

Table 1-4. Research papers investigating friction and binding from multiple factors of conventional elastomeric ligature, state, and/or second-order angulation (n=16).

Author	Friction Type (s)	Bracket (s)	Wires (inch)	Ligation Method (s)	Angulation (s)	State (s)	Conclusions	Limitations
Cunha et al 2011 [26]	Unknown	1 SS CB	0.018x0.025 (material unknown)	2 CEL NCEL (Coated) No ligation	N/A	1) Dry state 2) Artificial saliva (tested after 21 days)	-CEL and NCEL (Coated) < FR in dry state -CEL < FR in wet state -FR decreased with saliva (not statistically significant), suggesting time, heat, and humidity to cause elastic degradation	-Unknown bracket number for central incisor -Unknown friction type and wire material -Unclear if repeated testing of same brackets and wires -No ligature gun utilized -Tested $\theta = 0°$
Edwards et al 2011 [42]	SF	1 SS CB	0.019x0.025 SS	3 CEL NCEL (Coated)	4°	1) Dry state 2) Artificial saliva: 24hr, 1wk, 6wks 3) In vivo (patient's saliva): 24hr, 1wk, 6wks	-Modules in artificial saliva significantly < FR than dry state -Modules in vivo similar FR to dry state -Recommended patient's saliva as storage medium vs. artificial saliva -Under dry state, NCEL (Coated) had significantly > FR than other CELs	-Sample size different per state -Unknown bracket number for premolar and if consistent with in vivo testing -In vivo modules stored in artificial saliva 4hr before testing -Removed module from bracket in storage and re-

								ligate for testing -Changed wires every 15 tests -Tested only 1 angulation and θ_c not reported -No ligature gun utilized
Griffiths et al 2005 [43]	Unknown	1 SS SLB 1 SA CB *	0.018 SS 0.019x0.025 SS	SLB CEL (Round) NCEL (Coated) NCEL (Rectangular)	N/A	1) Dry state 2) Soak water bath 37°C 1hr	-SLB significantly < RS than all others (SLB at zero FR) -RS of CEL (Round) < NCEL (Coated) < NCEL (Rectangular) --Significant differences between all elastomers, some exceptions -Lubrication reduced FR with 0.018 inch wires and increased FR with 0.019x0.025 inch wires	-Small sample size -Unknown bracket number for premolar model -Unknown friction type -Unclear if repeated testing of same brackets and wires -No ligature gun utilized -Tested $\theta = 0°$
Hain et al 2003 [5]	SF	1 SS SLB 2 SS CB 1 MC CB	0.019x0.025 SS	SLB 2 CEL 2 NCEL (Coated) Loose SSL	N/A	1) Dry state 2) Pre-soaked 1hr human saliva	-Loose SSL had < FR overall -NCEL (Coated), both dry + wet, significantly < FR (up to 60%) than CEL -Saliva had greatest FR reduction -Figure 8 significantly > FR	-Unknown sample size and bracket number for premolar -Figure 8 and loose SSL only tested for 1 bracket -Loose SSL not practical clinically -Tested $\theta = 0°$

Haskova et al 2008 [44]	SF	1 CoCr CB	0.018 SS	3 CEL	0°, 5°, and 10°	1) Artificial saliva	-Ligation pattern highly significant in influencing frictional force -Frictional forces increased with increasing θ	-Small sample size -Applied lubricant with soft brush, non-standardized amount -θ_c not reported -Wet state only
Ho & West 1991 [45]	FR	1 SS CB 1 CE CB	0.16x0.16 NiTi 0.16x0.22 NiTi 0.17x0.25 NiTi 0.16x0.16 SS (3)^ 0.16x0.16 SS (3)^ 0.16x0.22 SS (3) 0.17x0.25 SS (3) 0.16x0.16 SS (8) 0.16x0.22 SS (8) 0.17x0.25 SS (8) 0.175x0.175 TMA 0.16x0.22 TMA 0.17x0.25 TMA Note: (#) represents # of strands and ^ different products	CEL	0°, 10°, and 20°	1) Dry state 2) Artificial saliva	-FR increased with θ -FR decreased with lubrication	-Small sample size -Unknown bracket number for lower anterior -θ_c not reported -No ligature gun utilized -Left CEL 6 days before testing
Husain et al 2011 [46]	KF	3 SS CB 1 Ti CB	0.16x0.22 SS 0.17x0.25 SS 0.18x0.25 SS	CEL SSL	N/A	1) Dry state 2) Artificial saliva	-CEL > FR than SSL -Frictional force for wet > than dry state for all wire and bracket combinations	-Unknown sample size and bracket number tested -Unclear if repeated use of brackets and wires -No ligature gun utilized -Tested θ = 0°

Jones & Bihi 2009 [47]	SF	1 SS CB	0.018 SS 0.019x0.025 SS	CEL NCEL (Slide)	N/A	1) Dry state 2) Artificial saliva 37°C 24hr	-NCEL (Slide) significantly < SF than CEL for both dry and wet states -Wet state had no effect on SF	-Small sample size -Tested $\theta = 0°$
Kusy & Whitley 2000 [48]	RS	2 SS CB	0.016x0.022 NiTi 0.016x0.022 CoCr 0.016x0.022 SS 0.016x0.022 TMA	SSL	-12° to +12° Note: Variable increments of 0.5°, 1°, and 2°	1) Dry state 2) Human saliva	-RS is independent of slot dimension once $\theta > \theta_c$ -For SS wires, saliva acts like an adhesive	-Small sample size -Unknown bracket number -No standard technique SSL placement
Read-ward et al 1997 [49]	SF	3 SS SLB 1 SS CB	0.020 SS 0.019x0.025 SS 0.021x0.025 SS	SLB SSL	0°, 5°, and 10°	1) Dry state 2) Human saliva	-Increases in θ resulted in increased SF for all bracket types, with presence of saliva having an inconsistent effect -SLB < FR in comparison to steel ligated CB only under certain conditions	-Small sample size -Unknown bracket number -θ_c not reported
Sims et al 1994 [50]	KF	1 SLB 2 SS CB *	0.018x0.025 SS	SLB CEL	0°, 2°, 4° and 6°	1) Dry state	-SLB consistently produced < FR than CBs -Increasing θ and torque produced almost linear increases in FR for all brackets, although increasing θ had the more profound effect on FR	-Small sample size -θ_c not reported -No ligature gun utilized -Dry state only
Thorstenson	RS	4 SS CB	0.018x0.025 SS	4 CEL	-12° to +12°	1) Dry state	-For a given bracket	-Small sample

& Kusy 2003 [51]				SSL	Note: Variable increments of 0.5° and 2°	2) Saliva	design, the ligation type and method did not alter the rate of BI -For overall RS, ligation type and method depended on θ: $\theta > \theta_c$ = FI > BI (ligation affected RS) $\theta >> \theta_c$ = BI > FR (ligation type and method minimal)	size -Unknown bracket number -Unknown if saliva human or artificial -Unclear if wire changed per test -Brackets tested with selective ligation methods -No ligature gun utilized -No conclusions made regarding state
Thorstenson & Kusy 2002 [52]	RS	6 SS SLB	0.018x0.025 SS	SLB	-9° to +9° Note: Variable increments of 1° and 2°	1) Dry state 2) Human saliva	-Above each θ_c, all brackets had BI that increased at similar rates as θ increased and were independent of bracket design -SLB represent a compromise between FR and control	-Small sample size -Unknown bracket number -Used one bracket data from previous study -Author: several iterations were necessary to bring all active data points above the experimental θ_c -Unclear if wires changed per test -No conclusions made regarding state

Thorstenson & Kusy 2001 [53]	RS	1 SS SLB 1 SS CB	0.018x0.025 SS	SLB closed SLB open + SSL SSL	-9° to +9° Note: Variable increments of 1° and 2°	1) Dry state 2) Human saliva	-In active configuration, all brackets increased RS as θ increased -At all θ, RS of SLB < CB because of absence of ligation force -RS slightly > wet than dry state	-Small sample size and unequal per group -Unknown bracket number -No standard technique SSL placement -Unclear if wires changed per test
Tselepis et al 1994 [11]	KF	1 SS CB 1 PC CB 1 PO CB 1 SA CB	0.016x0.022 NiTi 0.016x0.022 CoCr 0.016x0.022 SS 0.016x0.022 TMA	CEL	0° and 10°	1) Dry state 2) Artificial saliva	-FR increased with θ -Angulation had significant effect under dry and wet states -Lubrication significantly reduced FR (up to 60%) for both angulations, mainly SS and PC brackets	-Small sample size -Unknown bracket number for lower anterior -θ_c not reported -No ligature gun utilized -Left CEL 6 days before testing
Whitley & Kusy 2007 [54]	RS SF KF	1 CPTi CB	0.017x0.025 SS 0.017x0.025 TMA	SSL	-12° to +12° Note: Variable increments of 0.5° and 2°	1) Dry state 2) Human saliva	-In active region, RS increased as a function of θ -Model described for classical FR region, BI region, and notching/plastic region	-Small sample size -Unknown bracket number -No standard technique SSL placement -No conclusions made regarding state

* = Segment of brackets tested (i.e. more than 1 bracket)

1.7 Methodology

The majority of in-vitro studies believe the variability of experimental methods explain the inconsistency of study results.[19] For a thorough understanding, methods will be discussed separately for design of friction device, friction type, bracket and wire selections, ligation method, state, and angulation.

Historically, archwires slide through contact flats and investigators studied the influence of materials. Nowadays, orthodontic friction experiments commonly use a rigid device that either pulls a wire through a bracket slot or slides a bracket along a fixed wire,[1,2] where the force required for either situation is recorded. This 1D frictional measurement is at the wire level. There is no published research of a 3D model measuring resistance to sliding at the bracket level, which would correspond to the desired effect of resistance on an actual tooth. To effectively analyze tooth movements, an understanding of forces and moments in 3D space is essential.[3] Each research group has designed a friction device, usually associated with a complex description and many components. Unless a research group uses the same device, most devices are different from one another because of their specific arrangement. Other variable testing methods include selection of crosshead speed, load force, wire speed, distance, sample size, and control parameters to eliminate confounding variables. Although most of these variables differ per research group, some authors fail to report these parameters, leaving the reader to question the validity of the study results, along with difficult interpretation of the results and comparison with others.

Although volumes of friction literature exist, there is little consensus on the best way to quantify friction and establish clinical significance.[56] Of the 42 papers reviewed (Tables 1-1 to 1-4), 9 reported static friction, 9 reported both static and kinetic friction, 7 reported kinetic friction, 5 reported friction, 5 reported resistance to sliding, 3 unknown, 2 reported frictional resistance, 1 reported kinetic resistance to sliding, and 1 reported combined static friction, kinetic friction, and resistance to sliding. This variability was unexpected, as was the lack of definitions for friction type. Although some authors explained friction type, the stated definitions were undesirably variable. For example, static friction was described as the peak force,[1,22,23,31,36,42,47,49] the maximal initial rise,[5,14,15,28,30,44] the point at which the wire started to move,[38] the minimum force required for continuous free sliding,[6] or half the initial maximum on each plot[54].

To further illustrate variability, kinetic friction was assessed as the mean load from 4 readings taken after 2 minutes and 3 readings at further 2 minute intervals,[33] the mean of all peaks over 4mm with exception of the first peak,[11] the mean load from 6 readings taken at 30s intervals,[50] the lowest frictional force after 6s,[23] the mean over 10mm,[15] the mean force at 4mm,[1] measurements at 2, 5, 10mm displacement and averaged,[28,30] or dividing the average force data in the plateau region by 2[54]. Others evaluated kinetic friction as the mean over 100 data points on 5mm wire,[8] the maximum recorded over 11mm,[2] the mean registered at 5, 7, and 9mm of movement,[31] 50% of the difference between the force acting on the sensor during upward and downward motion,[29] averaging 5 readings at fixed intervals,[22] the mean between the beginning and end of motion,[26] or reading at the center of archwire[46]. Consistent friction definitions between authors are highly recommended to maintain consistency in outcome measurements.

Deviations continue with quantifying static and kinetic friction from a clinical perspective. Theoretically with classical "dry" friction, static friction is always stronger than kinetic friction.[9,40] As static friction is hard to measure, kinetic friction is measured for ease, but depends on the complexity with archwire-bracket debris, oral cavity debris, such as plaque and calculus, and salivary components including sugars, proteins, and enzymes.[4] Additionally, as teeth do not move continuously, Kusy and Whitley[4] conclude that both static and kinetic friction are important.

The variability in bracket selection was extensive, where brackets not only differed between manufacturers, but also in size, material, and prescription. The trend of evaluating modern brackets also makes it difficult comparing results to previous findings of older, likely discontinued, brackets. If brackets were tested individually, some authors specified the bracket number, others generalized, and some omitted this information in their publication. The inconsistency continued with the tested bracket number, for example, upper left central incisor,[36,44,47] upper right central incisor,[40] upper left canine,[1,33] or upper right canine[20]. Some authors generalized the tested bracket to upper central incisor,[23,26,31,38] upper canine,[22] upper premolar,[2,5,10,32,39,42] lower anterior,[11,45] or lower second premolar[37]. With a segment of brackets tested, authors studied upper right second premolar to central incisor,[28,30] upper right second molar to canine,[14] upper left canine-one premolar-molar,[50] or 10 upper left central incisor brackets[34]. Other authors using bracket segments were vague, resulting in uncertainty in which brackets were being tested. These segments included premolar-premolar-canine-premolar-premolar,[25] first molar-premolar or first-molar-premolar-premolar,[15] first molar-second premolar-first premolar, with first premolar tested,[43] upper premolar-premolar-canine,[8] or three lower incisors[6]. For sliding mechanics, the literature indeed illustrates a vast representation of tested brackets both individually and as a segment.

Wire selections greatly varied between manufacturers, material, size, and sometimes shape. Ligation method also varied between manufacturers, material, size, and placement technique. Although it is important to control the ligation force in a uniform manner[7] with a ligature gun or standardized technique, most experiments did not. Lubricant choice of artificial saliva, human saliva, or water-bath varied, including soaking time, if soaked. Different artificial saliva formulations exist,[11] as well as variations in properties of human saliva between individuals. The technique of saliva application varied from a brush, drop, to pump at various speeds. Angulation also consisted of a variable range of angulations tested.

It is evident that a significant number of variables are involved with friction studies.[11] Overall, these methodological differences make comparisons of the literature very difficult and could explain the inconsistent results.[23] Standardized testing protocols and full reporting by authors would be highly recommended for future studies.

1.8 Conclusion

The extreme variability of experimental methods used in the literature makes it difficult to compare results between friction studies. With the importance of evidence-based dentistry and high quality research, future studies of this caliber would be desirable. The effect of conventional elastomers on force and moment of a self-ligating bracket with angulation in the dry and wet states evaluated through a new 3D device will be studied.

1.9 References

1. Moore MM, Harrington E, Rock WP. Factors affecting friction in the pre-adjusted appliance. Eur J Orthod 2004;26:579-583.

2. Hamdan A, Rock P. The effect of different combinations of tip and torque on archwire/bracket friction. Eur J Orthod 2008;30:508-14.

3. Kusy RP. Influence of force systems on archwire-bracket combinations. Am J Orthod Dentofacial Orthop 2005;127:333-42.

4. Kusy RP, Whitley JQ. Friction between different wire-bracket configurations and materials. Semin Orthod 1997;3:166-77.

5. Hain M, Dhopatkar A, Rock P. The effect of ligation method on friction in sliding mechanics. Am J Orthod Dentofacial Orthop 2003;123:416-22.

6. Sirisaowaluk N, Kravchuk O, Ho CTC. The influence of ligation on frictional resistance to sliding during repeated displacement. Aust Orthod J 2006;22:141-6.

7. Articolo L, Kusy RP. Influence of angulation on the resistance to sliding in fixed appliances. Am J Orthod Dentofacial Orthop 1999;115:39-51.

8. Matarese G, Nucera R, Militi A, Mazza M, Portelli M, Festa F, Cordasco G. Evaluation of frictional forces during dental alignment: An experimental model with 3 nonleveled brackets. Am J Orthod Dentofacial Orthop 2008;133:708-15.

9. Frank CA, Nikolai RJ. A comparative study of frictional resistances between orthodontic bracket and arch wire. Am J Orthod 1980;78:593-609.

10. Khambay B, Millett D, McHugh S. Evaluation of methods of archwire ligation on frictional resistance. Eur J Orthod 2004;26:327-332.

11. Tselepis M, Brockhurst P, West VC. The dynamic frictional resistance between orthodontic brackets and arch wires. Am J Orthod Dentofacial Orthop 1994;106:131-8.

12. Stefanos S, Secchi AG, Coby G, Tanna N, Mante FK. Friction between various self-ligating brackets and archwire couples during sliding mechanics. Am J Orthod Dentofacial Orthop 2010;138:463-7.

13. Fleming PS, DiBiase AT, Lee RT. Self-ligating appliances: evolution or revolution? Aust Orthod J 2008;24:41-9.

14. Chimenti C, Franchi L, Di Giuseppe MG, Lucci M. Friction of orthodontic elastomeric ligatures with different dimensions. Angle Orthod 2005;75:421-5.

15. Taylor NG, Ison K. Frictional resistance between orthodontic brackets and archwires in the buccal segments. Angle Orthod 1996;66:215-222.

16. Kusy RP, Whitley JQ. Influence of archwire and bracket dimensions on sliding mechanics: derivations and determinations of the critical contact angles for binding. Eur J Orthod 1999;21:199-208.

17. Kusy RP. Ongoing innovations in biomechanics and materials for the new millennium. Angle Orthod 2000;70:366-76.

18. Burrow SJ. Friction and resistance to sliding in orthodontics: a critical review. Am J Orthod Dentofacial Orthop 2009;135:442-7.

19. Ehsani S, Mandich M, El-Bialy TH, Flores-Mir C. Frictional resistance in self-ligating orthodontic brackets and conventionally ligated brackets. Angle Orthod 2009;79:592-601.

20. Bednar JR, Gruendeman GW, Sandrik JL. A comparative study of frictional forces between orthodontic brackets and arch wires. Am J Orthod Dentofacial Orthop 1991;100:513-22.

21. Thorstenson GA, Kusy RP. Resistance to sliding of orthodontic brackets with bumps in the slot floors and walls: effects of second-order angulation. Dent Mater 2004;20:881-92.

22. Krishnan M, Kalathil S, Abraham KM. Comparative evaluation of frictional forces in active and passive self-ligating brackets with various archwire alloys. Am J Orthod Dentofacial Orthop 2009;136:675-82.

23. Downing A, Mccabe JF, Gordon PH. The effect of artificial saliva on the frictional forces between orthodontic brackets and archwires. Br J Orthod 1995;22:41-6.

24. Harradine, NWT. Self-ligating brackets: where are we now? J Orthod 2003;30:262-73.

25. Arun AV, Vaz AC. Frictional characteristics of the newer orthodontic elastomeric ligatures. Indian J Dent Res 2011;22:95-9.

26. Cunha AC, Marquezan M, Freitas AOA, Nojima LI. Frictional resistance of orthodontic wires tied with 3 types of elastomeric ligatures. Braz Oral Res 2011;25:526:30.

27. Miles PG. Self-ligating brackets in orthodontics: do they deliver what they claim? Aust Dent J 2009;54:9-11.

28. Baccetti T, Franchi L. Friction produced by types of elastomeric ligatures in treatment mechanics with the preadjusted appliance. Angle Orthod 2006;76:211-6.

29. Cordasco G, Farronato G, Festa F, Nucera R, Parazzoli E, Grossi GB. *In vitro* evaluation of the frictional forces between brackets and archwire with three passive self-ligating brackets. Eur J Orthod 2009;31:643-6.

30. Franchi L, Baccetti T, Camporesi M, Barbato E. Forces released during sliding mechanics with passive self-ligating brackets or non-conventional elastomeric ligatures. Am J Orthod Dentofacial Orthop 2008;133:87-90.

31. Gandini P, Orsi L, Bertoncini C, Massironi S, Franchi L. In vitro frictional forces generated by three different ligation methods. Angle Orthod 2008;78:917-21.

32. Khambay B, Millett D, McHugh S. Archwire seating forces produced by different ligation methods and their effect on frictional resistance. Eur J Orthod 2005;27:302-8.

33. Sims APT, Waters NE, Birnie DJ, Pethybridge RJ. A comparison of the forces required to produce tooth movement *in vitro* using two self-ligating brackets and a pre-adjusted bracket employing two types of ligation. Eur J Orthod 1993;15:377-85.

34. Tecco S, Tetè S, Festa F. Friction between archwires of different sizes, cross-section and alloy and brackets ligated with low-friction or conventional ligatures. Angle Orthod 2009;79:111-6.

35. Tecco S, Di lorio D, Cordasco G, Verrocchi I, Festa F. An *in vitro* investigation of the influence of self-ligating brackets, low friction ligatures, and archwire on frictional resistance. Eur J Orthod 2007;29:390-7.

36. Al-Mansouri N, Palmer G, Moles DR, Jones SP. The effects of lubrication on the static frictional resistance of orthodontic brackets. Aust Orthod J 2011;27:132-8.

37. Kusy RP, Whitley JQ, Prewitt MJ. Comparison of the frictional coefficients for selected archwire-bracket slot combinations in the dry and wet states. Angle Orthod 1991;61:293-302.

38. Dickson JAS, Jones SP, Davies EH. A comparison of the frictional characteristics of five initial alignment wires and stainless steel brackets at three bracket to wire angulations – an *in vitro* study. Br J Orthod 1994;21:15-22.

39. Pizzoni L, Ravnholt G, Melsen B. Frictional forces related to self-ligating brackets. Eur J Orthod 1998;20:283-291.

40. Redlich M, Mayer Y, Harari D, Lewinstein I. In vitro study of frictional forces during sliding mechanics of "reduced-friction" brackets. Am J Orthod Dentofacial Orthop 2003;124:69-73.

41. Thorstenson GA, Kusy RP. Effect of archwire size and material on the resistance to sliding of self-ligating brackets with second-order angulation in the dry state. Am J Orthod Dentofacial Orthop 2002;122:295-305.

42. Edwards IR, Spary DJ, Rock WP. The effect upon friction of the degradation of orthodontic elastomeric modules. Eur J Orthod 2011:1-7.

43. Griffiths HS, Sherriff M, Ireland AJ. Resistance to sliding with 3 types of elastomeric modules. Am J Orthod Dentofacial Orthop 2005;127:670-5.

44. Haskova JE, Palmer G, Jones SP. An *ex vivo* laboratory study to determine the static frictional resistance of a variable ligation orthodontic bracket system. J Orthod 2008;35:112-8.

45. Ho KS, West VC. Friction resistance between edgewise brackets and archwires. Aust Orthod J 1991;12:95-9.

46. Husain N, Kumar A. Frictional resistance between orthodontic brackets and archwire: an *in vitro* study. J Contemp Dent Pract 2011;12:91-9.

47. Jones SP, Bihi SB. Static frictional resistance with the slide low-friction elastomeric ligature system. Aust Orthod J 2009; 25:136-41.

48. Kusy RP, Whitley JQ. Resistance to sliding of orthodontic appliances in the dry and wet states: influence of archwire alloy, interbracket distance, and bracket engagement. J Biomed Mater Res 2000;52:797-811.

49. Read-ward GE, Jones SP, Davies EH. A comparison of self-ligating and conventional orthodontic bracket systems. Br J Orthod 1997;24:309-17.

50. Sims APT, Waters NE, Birnie DJ. A comparison of the forces required to produce tooth movement *ex vivo* through three types of pre-adjusted

brackets when subjected to determined tip or torque values. Br J Orthod 1994;21:367-73.

51. Thorstenson GA, Kusy RP. Effects of ligation type and method on the resistance to sliding of novel orthodontic brackets with second-order angulation in the dry and wet states. Angle Orthod 2003;73:418-30.

52. Thorstenson GA, Kusy RP. Comparison of resistance to sliding between different self-ligating brackets with second-order angulation in the dry and saliva states. Am J Orthod Dentofacial Orthop 2002;121:472-82.

53. Thorstenson GA, Kusy RP. Resistance to sliding of self-ligating brackets versus conventional stainless steel twin brackets with second-order angulation in the dry and wet (saliva) states. Am J Orthod Dentofacial Orthop 2001;120:361-70.

54. Whitley JQ, Kusy RP. Resistance to sliding of titanium brackets tested against stainless steel and beta-titanium archwires with second-order angulation in the dry and wet states. Am J Orthod Dentofacial Orthop 2007;131:400-11.

55. Henao SP, Kusy RP. Evaluation of the frictional resistance of conventional and self-ligating bracket designs using standardized archwires and dental typodonts. Angle Orthod 2004;74:202-11.

56. Swartz ML. Fact or friction: the clinical relevance of in vitro steady-state friction studies. J Clin Orthod 2007;41:427-32.

Chapter 2. Systematic Review of the Effect of Conventional Elastic Ligation

2.1 Introduction

Friction is defined as resistance to motion when one object moves tangentially against another.[1,2] In orthodontics, friction is a force that opposes every action to move teeth by sliding an archwire through a bracket.[3] The two types of friction during tooth movement are static friction, the resistance that prevents tooth movement, and kinetic friction, which is the force that resists motion.[4,5] As friction cannot be eliminated from orthodontic material interaction, controlling friction by maximizing efficiency and reproducibility of the appliance is the best solution[3] to produce light optimal forces for biologic tooth movement[6]. Friction in the bracket-archwire interaction is important in initial leveling, aligning, and sliding mechanics. Material modifications that reduce resistance to sliding (RS), such as novel ligation methods, are in high demand. Mathematically, RS may be approximated as an additive effect of friction (FR), binding (BI), and notching (NO), where FR is subdivided into plowing (PL), interlocking (IN), and shearing (SH) components[3,7,8]:

$$RS = (FR) + BI + NO = (PL + IN + SH) + BI + NO.$$

The slot of a conventional orthodontic bracket houses an archwire that must be secured in place with a form of ligation into the depth of the slot. The ligation method can significantly influence friction at the bracket-archwire interface. Conventional elastomeric ligatures (CEL) are widely used to engage archwires into brackets and have gained universal acceptance by the orthodontic profession,[9] especially due to their lower cost, convenience, and speed of application[6]. As a consequence of its elastic properties, modules are adversely affected by moisture and heat of the oral environment and succumb to force decay, hydrolysis, and permanent deformation over time.[6,10,11] Modified CEL to improve sliding properties are referred to as low-friction ligatures or non-conventional elastomeric ligatures (NCEL). These include injection molding to produce round cross-sectional modules vs. rectangular modules, fluoride-impregnated modules, polymeric coatings, lubricated modules, and modules that form a "tube-like" structure on conventional brackets. Alternatively, stainless steel ligatures (SSL) are a favorably hygienic although time-consuming form of ligation. Certainly, the variability in tightness of SSL can lead to either higher or lower frictional forces as a range of ligating forces exist between different operators.

Self-ligating brackets are ligatureless bracket systems that have a movable fourth wall that converts the slot into a tube thereby enclosing the archwire. Theoretically, self-ligating brackets are claimed to reduce friction levels in a considerable way because the wire can move freely in the slot. Self-ligating brackets have overcome limitations of CEL from efficiency, deformation, discoloration, and plaque control.[12] There are "active" self-ligating brackets where a spring clip presses against the archwire, such as Speed®, In-Ovation®, and Time®, and "passive" self-ligating brackets where the self-ligating clip does not press against the archwire, such as Damon®, Smart Clip®, Carriere®, and Opal®.

As elastic ligatures are widely used to ligate orthodontic archwires to conventional brackets, it would be beneficial to evaluate the available evidence regarding how they affect friction. The objective of this systematic review is to focus on elastic ligation and determine its effect on orthodontic wire frictional resistance and resistance to sliding.

2.2 Material and Methods

A computerized search was conducted of several electronic databases: MEDLINE (from 1946 to week 1 of September 2012), PubMed (from 1966 to week 1 of September 2012), EMBASE (from 1974 to 2012 week 26), and all Evidence-Based Medicine reviews (to September 8 2012). Terms used in this literature search were “bracket”, “ligation”, “friction”, “sliding”, and “elastics”. The selection and specific use of each term inside each database search were made with the help of a senior librarian specialized in health sciences database searches (Table 2-1).

The following inclusion criteria were chosen to initially select potential articles from the published abstract and/or title results:

- Solely an in-vitro study; and
- Use of elastic ligation on orthodontic brackets; and
- At least one comparable method of ligation, in addition to the elastic ligation, except self-ligation.

Two researchers independently made the selection process. Their results were compared and discrepancies were settled through discussion. When an article abstract did not provide enough information to make a decision, the article was obtained. All the article abstracts that appeared to meet the initial inclusion criteria were selected and the actual articles were collected.

The articles ultimately selected were chosen with the following additional inclusion criteria:

- Detailed materials and methods section; and
- The objective of determining frictional resistance or resistance to sliding of elastic ligatures.

Two researchers independently evaluated the actual articles and a consensus was reached regarding which articles fulfilled the final selection criteria. These articles were included in the systematic review. The reference lists of the retrieved articles were also hand-searched for additional relevant publications that may have been missed in the database searches.

Table 2-1. Search Results from Different Electronic Databases.

Database	Key Words	Results	Selected Abstracts	Selected Papers
MEDLINE	(1) (orthodontic brackets or bracket* or ligat*).mp; (2) exp Orthodontic Brackets; (3) 1 or 2; (4) exp Friction; (5) (friction* or sliding or slide*).mp; (6) 4 or 5; (7) elast*.ti,ab; (8) 3 and 6 and 7	106	38	27
PubMed	(("Orthodontic Brackets"[Mesh]) OR (orthodontic brackets OR bracket* OR ligat*)) AND (("Friction"[Mesh]) OR (friction* OR slide* OR sliding)) AND (elastic* OR elastomeric)	130	39	27
EMBASE	Same as MEDLINE	117	37	27
All EBM reviews[a] (Cochrane DSR, ACP Journal Club, DARE, CCTR, CMR, HTA, and NHSEED)	Same as MEDLINE	4	0	0
Hand search	Searched the reference lists of selected papers	2	2	2
Total		**359**	**116**	**83**
Duplicates			**75**	**54**
TOTAL after removing duplicates			**41**	**29**

[a] *EBM, Evidence-Based Medicine; DSR, Database of Systematic Reviews; ACP, American College of Physicians; DARE, Database of Abstracts of Reviews of Effects; CCTR, Cochrane Database of Trial Registration; CMR, Cochrane Methodology Register; HTA, Health Technology Assessment; NHSEED, National Health Service Economic Evaluation Database.*

2.3 Results

The search results and final number of abstracts and papers selected according to the inclusion criteria from the various databases are provided in Table 2-1.

From the forty-one studies that based on the abstracts seemed to be potentially useful, only twenty-nine (71%) actually fulfilled the final selection criteria after reading the complete article. The remaining twelve articles were rejected due to having no comparable method of ligation (1), unclear materials and methods (1), not addressing our frictional objective (9), and could not translate Chinese article (1).

Comparing the database results, MEDLINE, PubMed, and EMBASE showed the same twenty-seven finally selected papers. The hand search of the reference lists of the selected papers resulted in two additional papers.[36,37]

A summary of the selected papers is provided in Table 2-2, specifying key methodological characteristics and conclusions. Table 2-3 provided the list of excluded articles and the reasons for their exclusion.

Table 2-2. Summary of Selected Papers (n=29).

Author	Measurement Device	Total Number Tests	Bracket (s)	Wires (inch)	Ligation Method (s)	State (s)	Conclusions
Arun & Vaz 2011 [10]	-Jig assembly and Instron Machine -5 mm/min CS	30 (5/ligation)	5 brackets (4 PM, 1 C): -SS Ortho Organizers	0.019 x 0.025 SS	1) CEL Mini Stix (non-coated) 2) CEL QuiK-StiK (non-angled) 3) CEL small 4) CEL large 5) Super Slick Mini Stix (coated) 6) Easy-to-tie (angled)	Dry	-Easy-to-tie significantly < FR followed by Super Slick -Angulation and polymeric surface coating reduce FR compared to CEL -No difference FR with different ligature diameters
Baccetti & Franchi 2006 [13]	-Vicelike device and Instron Machine -15 mm/min CS	60 (30/ligation)	5 brackets (Tooth 15 to 11): -SS STEP	0.014 NiTi 0.019 x 0.025 SS	1) CEL (silver mini modules) 2) Slide	Dry 20°C ± 2°C	-Slide significantly < static and kinetic FR than CEL for both aligned and misaligned brackets
Bazakidou et al 1997 [14]	-Testing apparatus and Instron Machine -0.02 inch/min CS	1800 (10/grp)	PM bracket (0.018” and 0.022” slots): -SS Miniature Twin -Ceramic Signature -Composite Spirit -Composite Elan (only 0.018” slot) -Composite GAC -Composite	For 0.018” slot: 0.016 NiTi 0.016 SS 0.016 TMA 0.016 x 0.022 NiTi 0.016 x 0.022 SS 0.016 x 0.022 TMA For 0.022” slot: 0.018 NiTi 0.018 SS 0.018 TMA	1) CEL 2) SSL 0.010” (twist 7x)	Dry	For 0.018” slot: -CEL had significantly < frictional values 15/36 combinations and SSL had significantly < frictional values for 14/36 combinations For 0.022” slot: -CEL had significantly < frictional values for

			Silkon -Ceramic Starfire (only 0.022" slot)	0.017 x 0.025 NiTi 0.017 x 0.025 SS 0.017 x 0.025 TMA 0.019 x 0.025 NiTi 0.019 x 0.025 SS 0.019 x 0.025 TMA			26/54 combinations and SSL had significantly < frictional values for 23/54 combinations Overall: -2.7 to 3 times more variability for SSL than CEL -No conclusion as to whether CEL or SSL produced higher frictional resistance
Bednar et al 1991 [15]	-Rotating plastic disk and Instron Machine -12.7 mm/min CS	75 (3/grp)	Tooth 13 (0.018" slot): -Ceramic Allure -SS Mini-Diamond -SS SLB Speed	0.014 SS 0.016 SS 0.018 SS 0.016 x 0.016 SS 0.016 x 0.022 SS	1) SLB– 3 brackets tested 2) CEL (power 'O')- 3 brackets tested 3) SSL 0.010" (taut, slightly slackened) – 2 brackets tested for ceramic and 1 bracket tested for metal	Dry	-Lightly SSL had < FR than CEL for all brackets and wires
Bortoly et al 2008 [16]	-Universal testing machine (DL-500) -10 mm/min CS	280 (20/grp)	PM bracket: -SS Dyna-loc	0.019 x 0.025 SS	1) Power 'O' clear 2) Mini Stix clear 3) Sili-Ties clear 4) Super Slick clear 5) Teflon-coated 0.012" SSL (twist	1) Recent Stretching 25°C ± 2°C 2) Simulated Stretching Artificial Saliva 21 days, 37°C 3) Simulated	Recent Stretching: -Power O significantly > frictional force, followed by Mini Stix, Super Slick, Sili Ties, Teflon, and steel ligatures -Mini Stix and Super

					7x) only recent stretching 6) 0.012" SSL (twist 7x) only recent stretching	Stretching DR (8hr/16hr) 21 days, 37°C	Slick no significant differences, but Super Slick and Sili Ties significantly different Simulated Stretching Saliva and DR: -All CEL had significant reductions in frictional force, with more reduction power 'O' and least reduction Sili Ties and Super Slick -No significant differences in frictional forces after 21 days in each ligation grp -Teflon-coated SSL and SSL had lowest frictional forces, but CEL similar to SSL after 21 days
Chimenti et al 2005 [6]	-Vice-like device and Instron Machine -20 mm/min CS	50 (10/grp)	5 brackets (Tooth 17 to 13): -SS STEP	0.019 x 0.025 SS	1) CEL small (silver mini modules) 2) CEL medium (silver mini modules) 3) CEL large (silver mini modules) 4) CEL lubricated (clear)	Dry 20°C ± 2°C	-Small and medium CEL significantly < frictional forces than large CEL, ascribed mainly attributing to smaller thickness of ligature -No significant difference between small and medium CEL -Lubricated CEL

					5) CEL lubricated (gray)		significantly < frictional forces than non-lubricated CEL
Cordasco et al 2009 [17]	-Jig assembly and Carriage with 2 vertical rods -4 mm/min CS	36 (12/ligation)	3 same brackets: -SS SLB Damon 2	0.014 CuNiTi	1) Open Slide SLB + 0.010” SSL 2) Open Slide SLB + CEL (power ‘O’110) 3) SLB	Dry 37°C	-Passive SLB significantly < frictional forces than CEL or SSL -No significant difference frictional forces CEL vs. SSL -High standard deviation SSL
Cunha et al 2011 [11]	-Universal test machine -20 mm/min CS	60 (15/grp)	CI Bracket: -SS American Orthodontics	0.018 x 0.025 (material unknown)	1) CEL (TP) 2) CEL (3M) 3) Super Slick (coated) 4) No ligation	1) Dry 2) Artificial saliva (tested after 21 days)	-CEL and Super Slick < FR in dry state -CEL < FR in wet state -FR decreased with saliva (not statistically significant), suggesting time, heat, and humidity to cause elastic degradation
De Franco et al 1995 [18]	-Plexiglass friction apparatus -0.625 mm/min CS -Bracket-archwire angulations of 0, 5, 10, 15°	576 (6/grp)	Bracket: -SS Victory -Ceramic Polycrystalline Transcend -Ceramic Single Crystal Starfire	0.018 NiTi 0.018 SS 0.016 x 0.022 NiTi 0.016 x 0.022 SS	1) CEL clear 2) Teflon-coated SSL	Dry	-Teflon-coated SSL had < frictional forces than CEL for all combinations, mostly of which were significant -Ligature effect appears to be significant irrespective of bracket-archwire angulation
Dowling et al 1998 [19]	-Jig assembly and Instron Machine -1mm/min CS	300 (60/time point)	PM bracket: -SS Standard Twin (‘A’-	0.018 x 0.025 SS	1) CEL grey round 2) CEL clear	1) Dry 2) Water bath 37°C, testing	-CEL clear had significantly < frictional values

		(10/grp)	Company) -SS Minitwin		round (only Standard) 3) CEL orange round (only Standard) 4) CEL grey round fluoride-impregnated (only Standard) 5) CEL grey rectangular (only Standard)	weekly for 4 weeks	-When wet, CEL clear and CEL fluoride had had lowest failure load forces -When wet, overall reduction in failure load force, between 10-35%, for all ligatures
Edwards et al 1995 [20]	-Testing jig and Instron Machine -0.5 mm/min CS	80 (10/grp)	Bracket (0.018" slot): -SS Dentaurum	0.018 x 0.025 SS	1) CEL 2) CEL Figure 8 3) SSL 0.010" 4) Teflon-coated SSL 0.012"	1) Dry 2) Human Saliva 37°C 24hr (changed 12hr intervals)	-CEL Figure 8 had significantly > FR than any other ligation method, both dry and wet -Only CEL with saliva had significantly > frictional resistance than dry; frictional resistance increased when wet compared to dry for other ligation methods, but not significantly different -No significant differences in frictional resistance between CEL and SSL -Teflon-coated ligatures had lowest frictional forces (significantly when

							wet)
Franchi et al 2008 [21]	-Friction testing apparatus and Instron Machine -15 mm/min CS	180 (30/ligation)	5 brackets (Tooth 15 to 11): -SS SLB Carriere -SS SLB Damon 3 MX -SS SLB SmartClip -SS SLB Opal-M -SS STEP	0.019 x 0.025 SS	1) SLB 2) SLB 3) SLB 4) SLB 5) CEL (sliver mini modules) 6) Slide	Dry 20°C ± 2°C	-Slide significantly < frictional forces than CEL
Gandini et al 2008 [22]	-Steel support and Instron Machine -6 mm/min CS	60 (10/grp)	CI bracket: -SS SLB SmartClip -SS STEP	0.014 NiTi 0.019 x 0.025 SS	1) SLB 2) CEL (silver medium mini modules) 3) Slide (silver medium)	Dry 20°C ± 2°C	-Slide significantly < frictional forces than CEL
Griffiths et al 2005 [23]	-LR5K testing machine -5 mm/min CS -Buccal segment of 1 molar and 2 PM brackets	280 (10/grp)	First PM bracket: -SLB Damon 2 (slide closed and open) -Monocrystalline Inspire	0.018 SS 0.019 x 0.025 SS	1) SLB slide closed 2) Super Slick grey 3) Dispens-A-Stix round edged, grey 4) Lig-A-Ties square edged, grey	1) Dry 2) Soak water bath 37°C 1hr	- Damon brackets with slide closed significantly < resistance to sliding than all other combinations -Damon had virtually zero FR -Round < Super Slick < Rectangular resistance to sliding, except with Inspire and 0.018" wire, Super Slick highest frictional force when dry but lowest when wet -Significant differences between all 3 types

							elastic ligation, except 0.019 x 0.025" wires with Inspire when dry and Damon open slide when wet
Hain et al 2006 [24]	-Test jig and Instron Machine -20 mm/min CS	120 (15/grp)	PM bracket: -SS Victory Twin -SS SLB Speed -SS SLB Damon 2	0.019 x 0.025 SS	1) SLB 2) SLB 3) Regular uncoated^^ 4) Super-slick coated^^ 5) CEL silver (3M) 6) Easy-to-tie 7) Sili-Ties silicone-impregnated 8) Standard silver (American Orthodontics)	1) Pre-soaked human saliva 1hr 2) Saliva for a week at room temperature^^ 3) Super-slick not pre-soaked, drop of saliva	-Super-slick significantly < FR than all other ligation methods -CEL silver produced the most FR, followed by standard silver No significant differences: Regular uncoated, Easy-to-tie, and Sili-Ties -Prolonged saliva exposure significantly reduced FR for regular uncoated, not for Super-slick coated -Pre-soaked Super-slick significantly < FR than drop of saliva
Hain et al 2003 [4]	Same as above	Unknown	PM bracket: -SS SLB Speed -SS Victory Twin -Clarity Twin -SS Minitwin	Same as above	1) SLB 2) CEL grey 3) CEL grey Figure 8 (only Victory) 4) Super-Slick 5) Super-Slick Figure 8 (only Victory)	1) Dry 2) Pre-soaked human saliva 1hr	-Super-Slick had significantly < FR (by up to 60%) than CEL -Saliva lubrication had greatest frictional resistance reduction -Figure 8 had significantly >

					6) SSL twist taut, untwist 3 turns (only Victory)		frictional resistance -Reduction of FR with lubricated Super-Slick ligatures -Loose SSL had < frictional resistance overall
Husain et al 2011 [25]	-Jig assembly and Instron Machine -5 mm/min CS	Unknown	Bracket: 0.018” slot: -SS Dynalock -SS Minitwin 0.022” slot: -SS Ultra-Mini-Trim -Ti Dentaurum	For 0.018” slot: 0.016 x 0.022 SS 0.017 x 0.025 SS For 0.022” slot: 0.018 x 0.025 SS	1) CEL (ortho organisers) 2) 0.009” SSL	1) Dry 2) Artificial saliva	-CEL > FR than SSL -Frictional force for wet > than dry state for all wire and bracket combinations
Ioi et al 2009 [26]	-Adjustable tables and strain gauge -0.1 mm/sec CS	120 (10/grp)	4 brackets (first PM, C, LI, CI): -Plastic Clearbracket	0.019 x 0.025 SS	1) Plastic CEL 2) Clearsnap	Dry	-Clearsnap significantly < frictional forces than plastic CEL in both aligned and misaligned brackets
Jones & Bihi 2009 [27]	-Jig assembly and Instron Machine -0.5 mm/min CS	80 (10/grp)	Tooth 21: -SS Midi Diagonali	0.018 SS 0.019 x 0.025 SS	1) CEL (Glenroe Technologies) 2) Slide	1) Dry 2) Artificial saliva 37°C 24hr	-Slide significantly < static frictional resistance than CEL -Wet state no effect
Kahlon et al 2010 [28]	-Test jigs and Instron Machine -2 mm/sec CS	300 (30/grp)	5 brackets, all tooth 15: -SS SLB DMX -SS SLB In-Ovation R -SS Victory	0.016 x 0.022 SS 0.018 x 0.022 SS	1) SLB 2) SLB 3) CEL 4) Slide 5) SSL	Dry	-SLB DMX and SSL produced no measurable FR -Slide produced < FR than CEL for both wire sizes
Khambay et al 2005 [29]	-Nene testing machine -5 mm/min CS	100 (10/grp)	PM bracket: -SS Victory	**0.019 x 0.025 SS U shape **0.017 x 0.025 SS	1) purple 2) grey 3) Alastik	Fresh whole human saliva dripped 1	-0.017 x 0.025”: SSL smallest frictional force, significantly

				U shape	4) Super Slick 5) 0.09" SSL (twist 7x)	ml/min 25°C	lower than grey, Alastik, or Super Slick, but not from purple -Alastik frictional force significantly higher than most other ligations -0.019 x 0.025": SSL lowest frictional force, significantly lower than grey and Super Slick, but not from Alastik and purple
Khambay et al 2004 [30]	Same as above	200 (10/grp)	PM bracket: -SS preadjusted edgewise	0.017 x 0.025 SS 0.017 x 0.025 TMA 0.019 x 0.025 SS 0.019 x 0.025 TMA	Same as above	Same as above	-SSL had lowest frictional force for 0.017 x 0.025" SS, 0.019 x 0.025" SS, and 0.019 x 0.025" TMA wires -Purple ligatures had lowest frictional force for 0.017 x 0.025" TMA -No consistent pattern in frictional force across various combinations
Leander & Kumar 2011 [31]	-Instron Machine -10 mm/min CS -50g and 100g load	80 (40/load) (5/grp)	5 brackets (4 PM, 1 C): Bracket unknown	0.019 x 0.025 NiTi 0.019 x 0.025 SS 0.019 x 0.025 TMA 0.019 x 0.025 Timolium	1) CEL Dispense-A-Stix 2) Super Slick Ties	Wet	-Super Slick < FR (11%) for all archwires compared to CEL
Matarese et	-Jig assembly and	60 SLB	3 nonaligned	^0.014 NiTi	1) SLB	Dry 34°C	-No significant

al 2008 [32]	Carriage with 2 vertical rods -4 mm/min CS	(10/grp) 40 Mini Twin (only^ 10/grp)	second PM brackets: -SS SLB Damon 2 -SS Mini Twin	^0.016 NiTi (CEL + SSL) ^0.016 x 0.022 NiTi 0.0155 coaxial SS 0.016 SS 0.016 TMA	2) CEL (power 'O' 110) 3) 0.010" SSL (twist 7x)		differences between CEL and SSL, but only tested with 0.016" NiTi wire -High standard deviation SSL
Sims et al 1993 [33]	-Jig assembly and Instron Machine -0.5 mm/min CS	96 (6/grp)	Tooth 23: -SS Minitwin -SS SLB Activa -SS SLB Speed	0.016 x 0.022 SS 0.017 x 0.025 SS 0.018 x 0.025 SS 0.019 x 0.025 SS	1) SLB 2) SLB 3) CEL (Quickstiks) 4) CEL Figure 8 (Quickstiks)	Dry 20°C ± 2°C	-CEL Figure 8 significantly increased FR by a factor of 70-220% compared to CEL, except for 0.016 x 0.022" wire
Sirisaowaluk et al 2006 [34]	-Silicone jig -Free sliding of wire by filling container with water -Repeated vertical displacements applied to wire in simulated extraction site	64 (8/ligation)	*3 lower incisors (0.018" slot): -SS Diamond	0.016 x 0.022 SS	1) CEL (blue power 'O' modules) 2) Super Slick (red) 3) CEL (blue power 'O' modules) half (2 corners) engaged 4) CEL (blue power 'O' modules) figure 8 pattern 5) Teflon-coated ligature (twist taut, untwist ¼ turn) 6) SSL (twist as above) 7) Twist ligature (twist as above) in	Dry: CEL pre-stretched for 24hr	-CEL in figure 8 pattern had greatest frictional resistance to sliding and the only ligation that had no sliding with repeated vertical displacement -Both twist ligatures had least frictional resistance and showed free sliding -No significant differences: Super Slick and Teflon-coated, CEL 2 corners engaged and SSL -Significant differences: CEL > frictional resistance Teflon-

					occlusal to gingival direction 8) Twist ligature (twist as above) in gingival to occlusal direction		coated/SSL, Teflon-coated > frictional resistance than SSL, Super Slick and Teflon-coated < frictional resistance than CEL
Taylor & Ison 1996 [35]	-Jig assembly and Instron Machine -5 mm/min CS	Unknown	1 Molar and 1 or 2 PM brackets: -SS Standard Straight Wire ('A' Company) -SS SLB Activa -SS SLB Speed	0.018 SS 0.020 SS 0.016 x 0.022 SS 0.018 x 0.025 SS 0.019 x 0.025 SS	1) SLB 2) SLB 3) CEL 4) SSL 0.009" 5) Loose SSL 0.009"	1) Dry 20°C ± 2°C Only with 0.018 and 0.019 x 0.025" wires: 2) No ligation 3) Regular: CEL/SSL/Loose SSL 4) Pre-stretched CEL to double length 5) CEL left: 1 minute 1 day 1 week 3 weeks	For 0.018" wire: -SSL significantly < frictional forces than CEL un-stretched -Pre-stretched CEL or loose SSL had significantly < frictional resistance than CEL un-stretched or SSL -Low frictional resistance found without PM ligation for both wires -Other than < frictional forces with loose SSL, differences in frictional forces with other ligation methods not significant -Frictional forces declined slowly over time, with reduction larger for rectangular wires
Tecco et al	-Mechanical	400	Tooth 21:	0.014 NiTi	1) CEL (Leone)	Dry 34°C	-Slide significantly <

2009 [36]	testing machine (Model Lloyd 30K) -0.5 mm/min CS	(10/grp)	10 aligned brackets	0.016 NiTi 0.018 SS 0.016 x 0.022 NiTi 0.016 x 0.022 SS 0.017 x 0.025 NiTi 0.017 x 0.025 TMA 0.017 x 0.025 SS 0.019 x 0.025 NiTi 0.019 x 0.025 SS	2) Slide small 3) Slide medium 4) Slide large		frictional resistance than CEL with round archwires only, not rectangular archwires -Different sizes do not cause differences in frictional resistance
Tecoo et al 2007 [37]	Same as above	400 (20/grp)	10 aligned brackets: -SS Victory -SS SLB Damon 2 -SLB Time Plus	0.016 NiTi 0.016 x 0.022 NiTi 0.017 x 0.025 TMA 0.019 x 0.025 NiTi 0.019 x 0.025 SS	1) SLB 2) SLB 3) CEL (ligature ringlet) 4) Slide	Same as above	-Slide had < FR than CEL for all wires

All brackets had nominal slot dimension of 0.022”, unless otherwise noted.
All brackets tested were maxillary, except for *.
All straight wires tested, except for **.

Table 2-3. Articles not selected from the final selection criteria and reason for exclusion.

Reason for Exclusion	Article
No comparable method of ligation	Henao [1]
Unclear materials and methods	Frank [2]
Did not study frictional resistance or resistance to sliding	Reznikov [3]
	Baccetti [4]
	Franchi [5]
	Baccetti [6]
	Baccetti [7]
	Franchi [8]
	Camporesi [9]
	Franchi [10]
	Berger [11]
Could not translate Chinese paper	Lin [12]

2.4 Discussion

To assess frictional resistance or resistance to sliding, a vast array of measurement devices and experimental protocol's were described. For instance, although most studies used a Universal Instron Machine, the crosshead speed varied from 0.1 to 20 mm/min. Largely, studies did not analyze static and kinetic friction separately. Authors assessed either static or kinetic friction, although reporting which was most relevant was vague, as well as specific measurement definitions. This systematic review illustrated a broad representation of tested brackets, both individually and as a segment, including various manufacturers. A sample size of ten per group was considered adequate to enhance study validity and minimize experimental errors. When sample size was reported, nine out of the twenty-nine papers or 31% had a sample size of less than ten per group. Most experiments were tested in the dry state. On the other hand, twelve out of twenty-nine papers or 41% tested in a wet state, such as a water bath, artificial saliva, or human saliva. The variability in wet state continued with soaking time and application. Overall, making direct comparisons of the elastic ligation conclusions was complex due to the wide range of experimental setups.

Ligation method also varied from manufacturers, material, and size to placement technique. Although it is important to control the ligation force in a uniform manner with a ligature gun for CEL or standardized technique for SSL, most experiments did not. With papers evaluating SSL versus CEL, 53% concluded SSL to have less frictional forces than CEL and 47% stated similar frictional resistance between SSL and CEL. Additionally, some authors reported a high standard deviation for SSL application, where variability for SSL was up to three times more than CEL. The experiments studying NCEL versus CEL had more variable outcomes. Generally, 74% of authors specified NCEL to have less frictional resistance than CEL. On the other hand, 17% and 9% of authors identified similar friction or NCEL to have greater frictional forces than CEL, respectively. Noteworthy, the NCEL and CEL of each experiment varied, such as brand, modification, size, color, and application. It is evident that a significant number of variables, including ligation method, are involved with examining frictional resistance.[38] As most authors discussed, the methodological differences in studies make comparisons of the literature very difficult and could explain the inconsistent results.[39]

Despite the difficulty in interpreting in-vitro studies to in-vivo reality, authors made great efforts for experimental conditions to reflect clinical situations and thereby obtain clinically useful information. However, caution is warranted in extrapolating in–vitro findings to in-vivo behavior. For instance, it is uncertain how results for isolated brackets, as most authors investigated, apply to friction in the buccal segments. Generally, studies did not consider physiological functions such as chewing, swallowing, and speaking, second-order angulations or binding between the archwire and bracket, and the effect of time and oral environment.

2.5 Conclusion

In summary, the wide range of experimental setups made direct comparisons difficult. Specifically, SSL had less or similar frictional resistance than CEL, whereas NCEL generally had less frictional resistance against CEL. Overall, these findings represented a trend in frictional resistance or resistance to sliding across various ligation combinations. Future studies with standardized methodologies and large sample size are highly recommended to make comprehensive conclusions.

2.6 References

1. Articolo L, Kusy RP. Influence of angulation on the resistance to sliding in fixed appliances. Am J Orthod Dentofacial Orthop 1999;115:39-51.

2. Kusy RP. Influence of force systems on archwire-bracket combinations. Am J Orthod Dentofacial Orthop 2005;127:333-42.

3. Kusy RP, Whitley JQ. Friction between different wire-bracket configurations and materials. Semin Orthod 1997;3:166-77.

4. Hain M, Dhopatkar A, Rock P. The effect of ligation method on friction in sliding mechanics. Am J Orthod Dentofacial Orthop 2003;123:416-22.

5. Frank CA, Nikolai RJ. A comparative study of frictional resistances between orthodontic bracket and arch wire. Am J Orthod 1980;78:593-609.

6. Chimenti C, Franchi L, Di Giuseppe MG, Lucci M. Friction of orthodontic elastomeric ligatures with different dimensions. Angle Orthod 2005;75:421-5.

7. Kusy RP, Whitley JQ. Influence of archwire and bracket dimensions on sliding mechanics: derivations and determinations of the critical contact angles for binding. Eur J Orthod 1999;21:199-208.

8. Kusy RP. Ongoing innovations in biomechanics and materials for the new millennium. Angle Orthod 2000;70:366-76.

9. Marques ISV, Araújo AM, Gurgel JA, Normando D. Debris, roughness and friction of stainless steel archwires following clinical use. Angle Orthod 2010;80:521-7.

10. Arun AV, Vaz AC. Frictional characteristics of the newer orthodontic elastomeric ligatures. Indian J Dent Res 2011;22:95-9.

11. Cunha AC, Marquezan M, Freitas AOA, Nojima LI. Frictional resistance of orthodontic wires tied with 3 types of elastomeric ligatures. Braz Oral Res 2011;25:526:30.

12. Fleming PS, DiBiase AT, Lee RT. Self-ligating appliances: evolution or revolution? Aust Orthod J 2008;24:41-9.

13. Baccetti T, Franchi L. Friction produced by types of elastomeric ligatures in treatment mechanics with the preadjusted appliance. Angle Orthod 2006;76:211-6.

14. Bazakidou E, Nanda RS, Duncanson MG, Sinha P. Evaluation of frictional resistance in esthetic brackets. Am J Orthod Dentofacial Orthop 1997;112:138-44.

15. Bednar JR, Gruendeman GW, Sandrik JL. A comparative study of frictional forces between orthodontic brackets and arch wires. Am J Orthod Dentofacial Orthop 1991;100:513-22.

16. Bortoly TG, Guerrero AP, Rached RN, Tanaka O, Guariza-Filho O, Rosa EAR. Sliding resistance with esthetic ligatures: an in-vitro study. Am J Orthod Dentofacial Orthop 2008;133:340.e1-340.e7.

17. Cordasco G, Farronato G, Festa F, Nucera R, Parazzoli E, Grossi GB. *In vitro* evaluation of the frictional forces between brackets and archwire with three passive self-ligating brackets. Eur J Orthod 2009;31:643-6.

18. De Franco DJ, Spiller RE, von Fraunhofer JA. Frictional resistances using teflon-coated ligatures with various bracket-archwire combinations. Angle Orthod 1995;65:63-74.

19. Dowling PA, Jones WB, Lagerstrom L, Sandham JA. An investigation into the behavioural characteristics of orthodontic elastomeric modules. Br J Orthod 1998;25:197-202.

20. Edwards GD, Davies EH, Jones SP. The *ex-vivo* effect of ligation technique on the static frictional resistance of stainless steel brackets and archwires. Br J Orthod 1995;22:145-53.

21. Franchi L, Baccetti T, Camporesi M, Barbato E. Forces released during sliding mechanics with passive self-ligating brackets or nonconventional elastomeric ligatures. Am J Orthod Dentofacial Orthop 2008;133:87-90.

22. Gandini P, Orsi L, Bertoncini C, Massironi S, Franchi L. In vitro frictional forces generated by three different ligation methods. Angle Orthod 2008;78:917-21.

23. Griffiths HS, Sherriff M, Ireland AJ. Resistance to sliding with 3 types of elastomeric modules. Am J Orthod Dentofacial Orthop 2005;127:670-5.

24. Hain M, Dhopatkar A, Rock P. A comparison of different ligation methods on friction. Am J Orthod Dentofacial Orthop 2006;130:666-70

25. Husain N, Kumar A. Frictional resistance between orthodontic brackets and archwire: an *in vitro* study. J Contemp Dent Pract 2011;12:91-9.

26. Ioi H, Yanase Y, Uehara M, Hara A, Nakata S, Nakasima A. Frictional resistance in plastic preadjusted brackets ligated with low-friction and conventional elastomeric ligatures. J Orthod 2009;36:17-22.

27. Jones S, Bihi SB. Static frictional resistance with the slide low-friction elastomeric ligature system. Aust Orthod J 2009;25:136-41.

28. Kahlon S, Rinchuse D, Robison JM, Close JM. In-vitro evaluation of frictional resistance with 5 ligation methods and gianelly-type working wires. Am J Orthod Dentofacial Orthop 2010;138:67-71.

29. Khambay B, Millett D, McHugh S. Archwire seating forces produced by different ligation methods and their effect on frictional resistance. Eur J Orthod 2005;27:302-8.

30. Khambay B, Millett D, McHugh S. Evaluation of methods of archwire ligation on frictional resistance. Eur J Orthod 2004;26:327-32.

31. Leander D, Kumar JK. Comparative evaluation of frictional characteristics of coated low friction ligatures – super slick ties with conventional uncoated ligatures. Indian J Dent Res 2011;22:90-4.

32. Matarese G, Nucera R, Militi A, Mazza M, Portelli M, Festa F, Cordasco G. Evaluation of frictional forces during dental alignment: an experimental model with 3 nonleveled brackets. Am J Orthod Dentofacial Orthop 2008;133:708-15.

33. Sims APT, Waters NE, Birnie DJ, Pethybridge RJ. A comparison of the forces required to produce tooth movement *in vitro* using two self-ligating brackets and a pre-adjusted bracket employing two types of ligation. Eur J Orthod 1993;15:377-85.

34. Sirisaowaluk N, Kravchuk O, Ho CTC. The influence of ligation on frictional resistance to sliding during repeated displacement. Aust Orthod J 2006;22:141-6.

35. Taylor NG, Ison K. Frictional resistance between orthodontic brackets and archwires in the buccal segments. Angle Orthod 1996;66:215-22.

36. Tecco S, Tetè S, Festa F. Friction between archwires of different sizes, cross-section and alloy and brackets ligated with low-friction or conventional ligatures. Angle Orthod 2009;79:111-6.

37. Tecco S, Di Iorio D, Cordasco G, Verrocchi I, Festa F. An *in vitro* investigation of the influence of self-ligating brackets, low friction ligatures, and archwire on frictional resistance. Eur J Orthod 2007;29:390-7.

38. Tselepis M, Brockhurst P, West VC. The dynamic frictional resistance between orthodontic brackets and arch wires. Am J Orthod Dentofacial Orthop 1994;106:131-8.

39. Downing A, Mccabe JF, Gordon PH. The effect of artificial saliva on the frictional forces between orthodontic brackets and archwires. Br J Orthod 1995;22:41-6.

2.7 References for Table 2-3

1. Henao SP, Kusy RP. Frictional evaluations of dental typodont models using four self-ligating designs and a conventional design. Angle Orthod 2005;75:75-85.

2. Frank CA, Nikolai RJ. A comparative study of frictional resistances between orthodontic bracket and arch wire. Am J Orthod 1980;78:593-609.

3. Reznikov N, Har-Zion G, Barkana I, Abed Y, Redlich M. Measurement of friction forces between stainless steel wires and "reduced-friction" self-ligating brackets. Am J Orthod Dentofacial Orthop 2010;138:330-8.

4. Baccetti T, Franchi L, Camporesi M, Defraia E. Orthodontic forces released by low-friction versus conventional systems during alignment of apically or buccally malposed teeth. Eur J Orthod 2011;33:50-4.

5. Franchi L, Baccetti T, Camporesi M, Giuntini V. Forces released by nonconventional bracket or ligature systems during alignment of buccally displaced teeth. Am J Orthod Dentofacial Orthop 2009;136:316.e1-6.

6. Baccetti T, Franchi L, Camporesi M, Defraia E, Barbato E. Forces produced by different nonconventional bracket or ligature systems during alignment of apically displaced teeth. Angle Orthod 2009;79:533-9.

7. Baccetti T, Franchi L, Camporesi M. Forces in the presence of ceramic versus stainless steel brackets with unconventional vs conventional ligatures. Angle Orthod 2008;78:120-4.

8. Franchi L, Baccetti T, Camporesi M. An experimental study on the forces released by ceramic preadjusted brackets with low friction vs. conventional elastomeric ligatures. Prog Orthod 2007;8:294-9.

9. Camporesi M, Baccetti T, Franchi L. Forces released by esthetic preadjusted appliances with low-friction and conventional elastomeric ligatures. Am J Orthod Dentofacial Orthop 2007;131:772-5.

10. Franchi L, Baccetti T. Forces released during alignment with a preadjusted appliance with different types of elastomeric ligatures. Am J Orthod Dentofacial Orthop 2006;129:687-90.

11. Berger JL. The influence of the SPEED bracket's self-ligating design on force levels in tooth movement: a comparative in vitro study. Am J Orthod Dentofacial Orthop 1990;97:219-28.

12. Lin HP, Wu JY. A study of frictional resistance of archwires and ligating methods. Shanghai Kou Qiang Yi Xue 2005;14:164-8.

Chapter 3. The Effect of Conventional Elastomers on Force and Moment of a Self-Ligating Orthodontic Bracket with Second-Order Angulation in the Dry and Wet States evaluated through a new 3D Friction Device

3.1 Introduction

Friction is a force that resists the movement between two objects and occurs tangent to the plane of contact.[1,2] In orthodontics, friction opposes every action to move teeth with sliding mechanics.[3,4] As a multi-factorial phenomenon, Nanda[5] has identified 21 variables contributing to frictional force between a bracket and an archwire in sliding mechanics, illustrated in Figure 3-1.

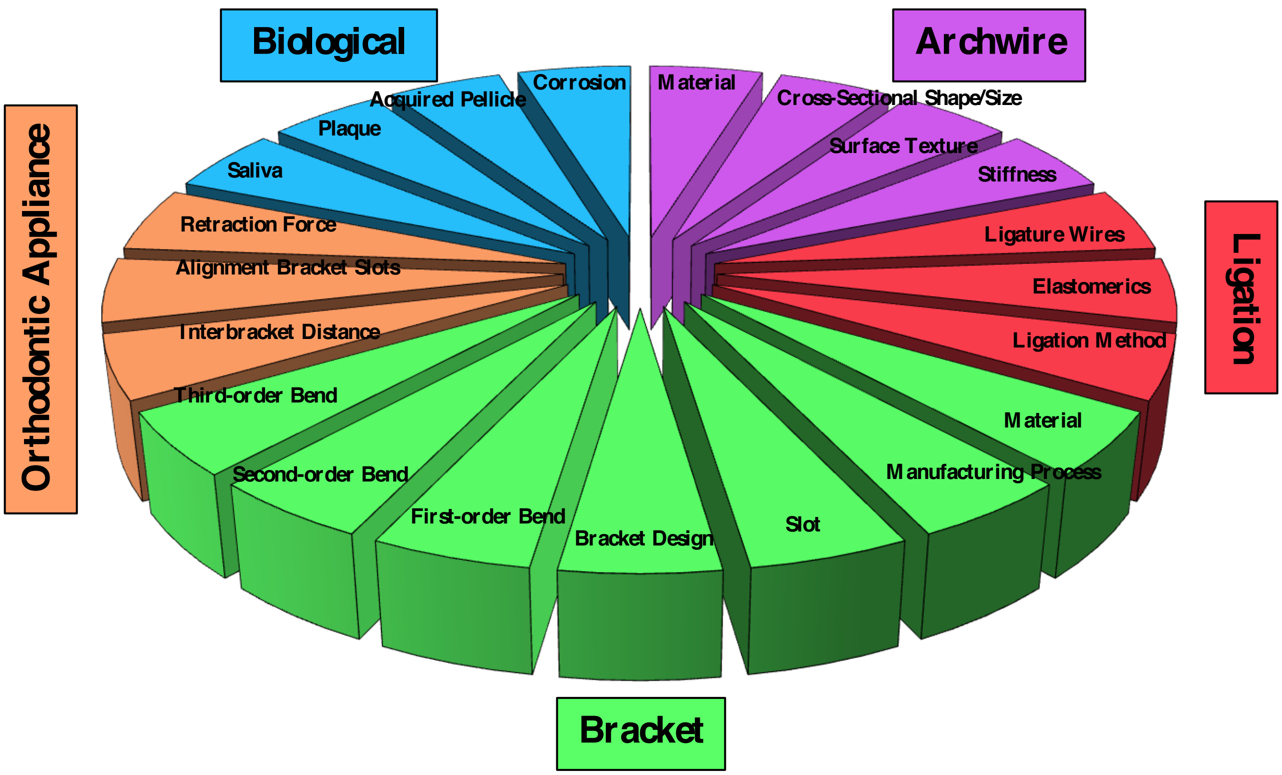


Figure 3-1. Variables affecting frictional force during tooth movement.[5]

While friction cannot be eliminated from orthodontic material interaction, Kusy and Whitey[3] consider controlling friction by maximizing efficiency and reproducibility of the appliance to be the best solution. Desirably, light optimal forces are produced for tooth movement[6], including the leveling, aligning, and space closure phases of treatment[7].

Friction in the bracket/archwire interaction is of great interest in sliding mechanics. During tooth movement, particularly canine retraction, changes in the tip angle of the tooth lead to variations in the underlying nature of this interaction. Resistance to sliding (RS) may be approximated as an additive effect of friction (FR), binding (BI), and notching (NO), where FR is subdivided into plowing (PL), interlocking (IN), and shearing (SH) components.[3,8,9] The overall expression of resistance to sliding is[3]:

$$RS = (FR) + BI + NO = (PL + IN + SH) + BI + NO.$$

Friction involves contact with one edge of the slot, where the wire is not completely engaged, and a single normal force on the wire. Binding, still a friction interaction, involves simultaneous contact of the wire with opposite edge corners of the slot to produce a couple interaction.[9] The normal forces of this couple balance and cancel, but each produces additive friction force that is proportional to the tip angle. An illustration in Figure 3-2 portrays these normal and friction forces for sliding mechanics. Notching, the ultimate manifestation of binding, involves plastic deformation to the wire or slot surfaces.[9]

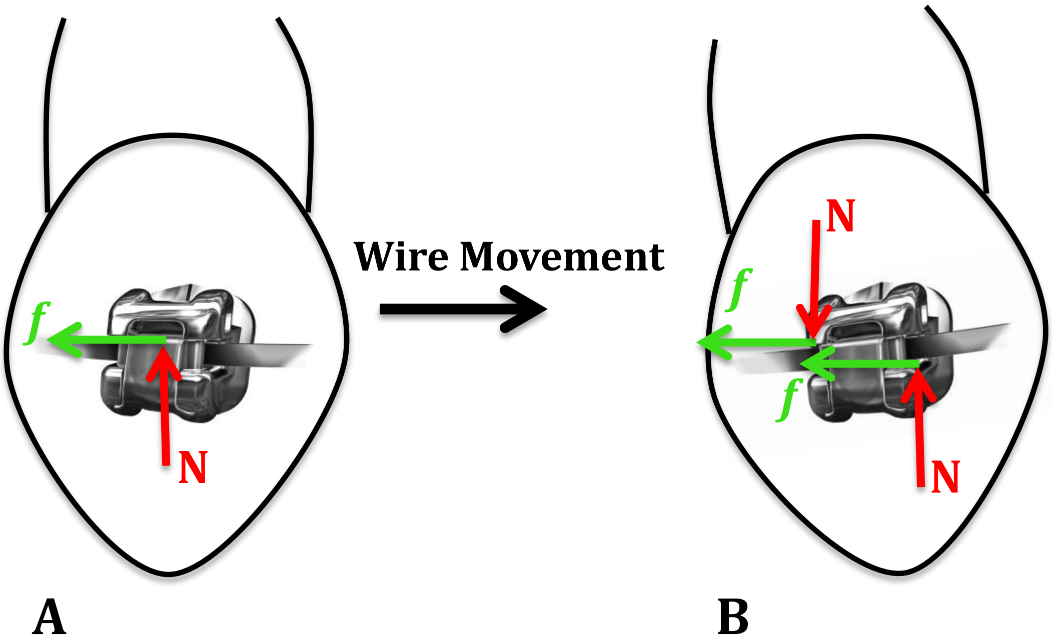


Figure 3-2. Sequence of canine movement during retraction with sliding mechanics. **A,** Friction involves the normal component of force (N) and the friction force to movement (*f*). **B,** Binding, when the bracket tips until the diagonally opposite corners of the bracket contact the wire, involves two equal and opposite normal forces that cancel and two friction forces. Images adapted from Nanda.[5]

Additionally, the components of resistance to sliding are illustrated in Figure 3-3, where the critical contact angle for binding differentiates the friction dominated (independent of angulation) versus binding dominated (linearly dependent on angulation) regions.[9]

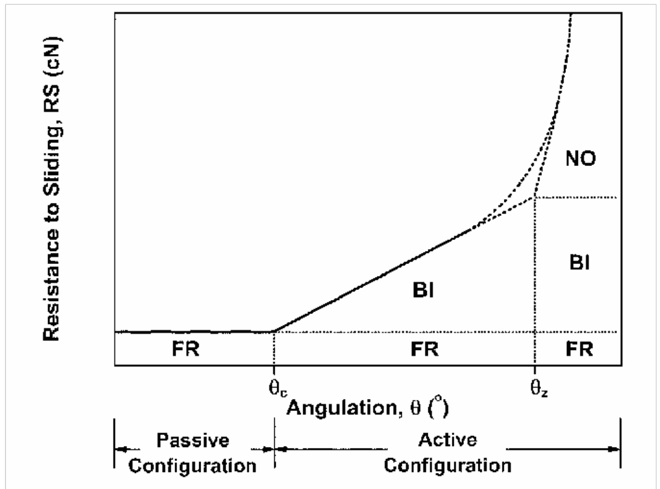


Figure 3-3. A schematic diagram of resistance to sliding components: friction, binding, and notching, where θ_c denotes the critical contact angle for binding and θ_z denotes the critical contact angle for notching. Image copied from Kusy.[9]

As friction is one component of resistance to sliding, these terms are not interchangeable. Notably, only Robert Kusy and his colleagues have identified binding in the literature, whereas other authors simply used the term friction. The relative importance of each term depends on a number of variables. The key variables are ligation method and the orientation of the bracket tip or in other words, second-order angulation (θ). Material modifications from manufacturers that reduce resistance to sliding are in high demand. A moment is defined as the rotational potential of a force with respect to a specific axis or point.[2] Although the topic of friction has produced numerous publications,[10] the evaluation of moment produced by a bracket has not been published.

The slot of a conventional bracket houses an archwire that must be secured with a form of ligation. Although various ligation methods exist, conventional elastomeric ligatures (CEL) remain popular among clinicians,[11] due to their lower cost, convenience, and speed of application,[6] and among patients because of comfort, hygiene, and color selection[12,13]. Elastic modules are adversely affected by moisture and heat of the oral environment and succumb to force decay, hydrolysis, and permanent deformation over time.[6,12,13] Self-ligating brackets have a movable fourth wall that converts the slot into a tube thereby enclosing the archwire. Self-ligating brackets have overcome some of the limitations of CEL from chair time efficiency, elastomer deformation, discoloration, plaque control, and debatably friction.[14] A recent systematic review comparing self-ligating bracket and conventional bracket concluded that in an ideally aligned arch, self-ligating bracket produced lower friction with small round archwires in the absence of tipping and/or torque.[15] With moderate malocclusion and large rectangular wires, no sufficient evidence was found for self-ligating bracket to produce lower friction than conventional bracket in the presence of tipping and/or torque.[15] To complicate matters further, practitioners commonly apply CEL over a self-ligating bracket due to a patient's request for colors, thereby transforming the self-ligating bracket to a conventional bracket.

The nature of ligation and angulation of bracket-wire interface can significantly influence friction,[16,17] and binding, where increases in ligation force[16] or angulation[7] increase resistance to sliding. Experimental testing in dry and wet environments is beneficial to simulate intra-oral conditions. As water and artificial saliva are not valid substitutes for clinical application, human saliva is the recommended means of lubrication.[3]

Current in-vitro experiments pull a wire through a bracket slot or slide a bracket along a fixed wire[18,19] and record one-dimensional (1D) frictional data at the wire level. No three-dimensional (3D) model measuring force and moment at the desired bracket level has been published, although intuitively an understanding of force and moment in 3D space is essential[2] to effectively analyze tooth movements.

The aims of this study are to:

1. Utilize a novel 3D device to evaluate resistance to sliding during canine retraction on a continuous archwire.
2. To compare the 3D results with past research.
3. To evaluate the main effects of elastomer ligation, state, angulation, and interactions by studying the result of CEL on the force and moment of a self-ligating bracket with angulation in the dry and wet states.
4. To determine the dominant influences on force and moment and to quantify amount.
5. To calculate the coefficient of kinetic friction and compare to literature.

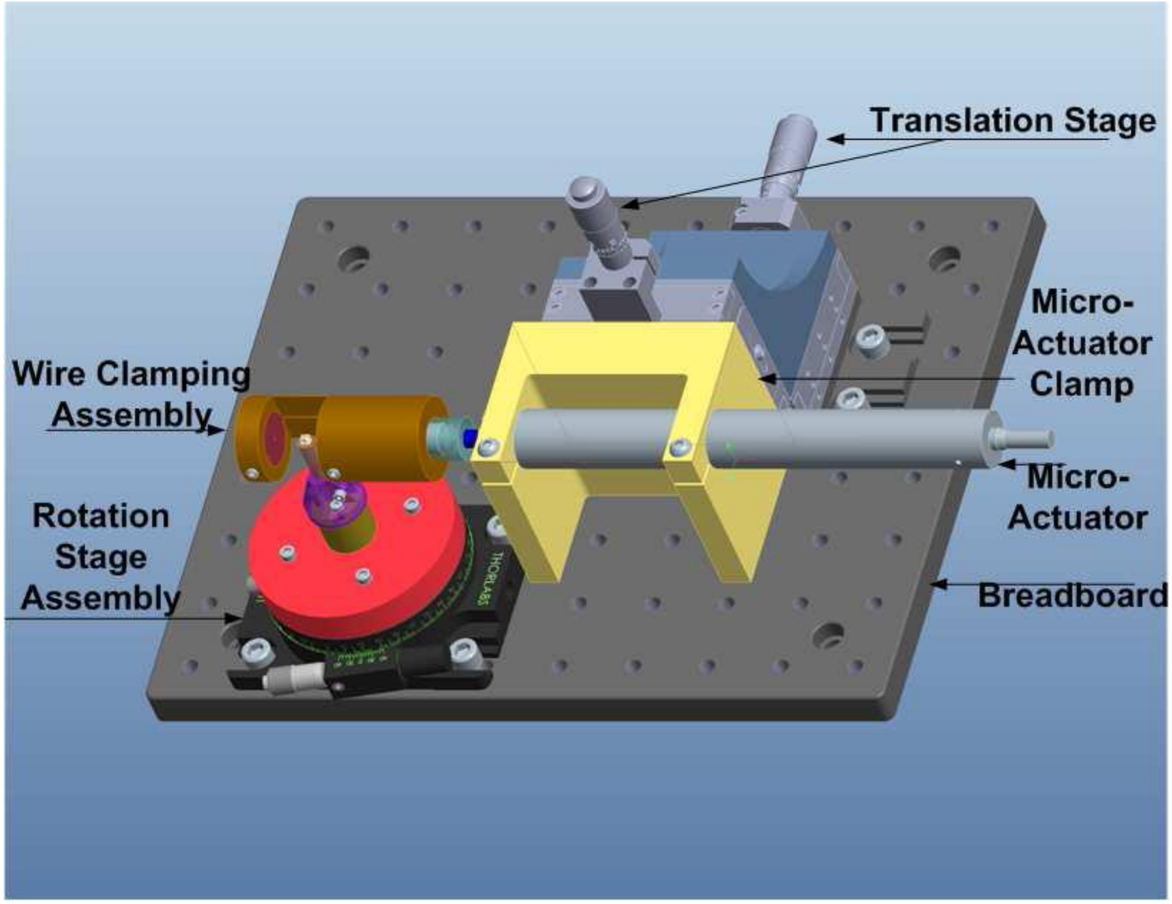
3.2 Material and Methods

To maintain a consistent technique, the primary investigator (MF) completed all procedures at room temperature.

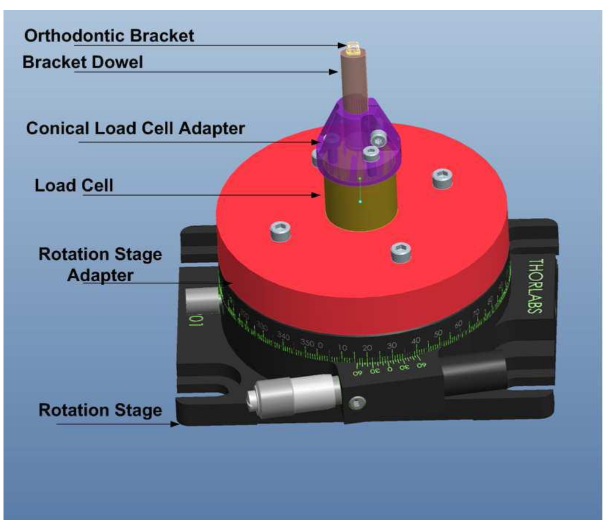
3.2.1 The Testing Apparatus

A novel approach to studying friction in-vitro evaluates force and moment interactions in 3D, specifically measuring kinetic friction and moment around the bracket level, not at the wire level as past literature has dictated. The Mechanical Engineering Department at the University of Alberta engineered this device, as shown in Figure 3-4, to measure force and moment of an orthodontic bracket and dowel pair by utilizing a six-axis load cell. The movement of an archwire through a bracket, in the x axis, is achieved by using a programmable micro-actuator that is controlled by a motor controller. The orientation of the bracket relative to the wire is controlled using a programmable rotating stage. Two manual translating stages are utilized in the design of the friction device to control the Y and Z position of the wire in the slot. The wire velocity, wire distance, and angulation are controlled digitally in an experiment control panel. The device initializes according to parameters of a customized configuration file for each bracket and dowel pair. The movement of the micro-actuator and rotary turntable are controlled by settings in the configuration file. These include translation and rotation increments, total movement, and speed. The configuration file also contains settings for the data acquisition (DAQ) system, including speed and averaging settings, load cell overload warning settings, and data file headers. The voltage data acquired from the load cell DAQ is converted to force and moment data. This data is transformed from the load cell frame to the bracket frame and the output data is saved as a log file for later processing.

A



B



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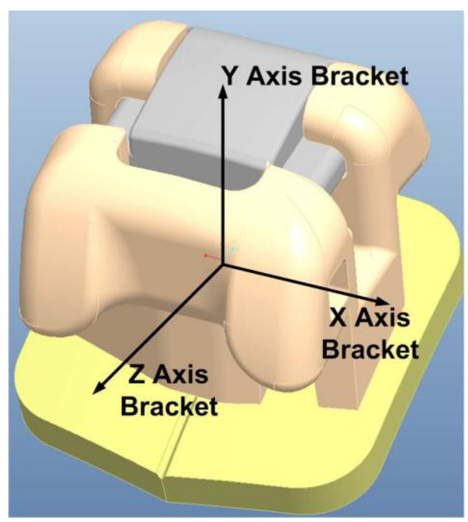

Figure 3-4. Novel 3D friction device. **A,** Friction device assembly. **B,** Bracket mounting mechanism. **C,** Bracket coordinate system.

3.2.2 Preparation of the Bracket and Dowel Pair

Based on the standard deviation of similar research a sample size of 65 per ligation group was warranted.[20,21] Refer to Appendix A for specific sample size calculation. A total of 130 stainless steel self-ligating bracket of upper left canine tooth (Damon Q, Ormco, Orange CA) with nominal slot size of 0.022", +7° torque, +5° angulation, and 0° rotation prescription were assembled. Stainless steel cylindrical (1/4" diameter, 1-1/4" length) dowel pins (McMaster-Carr) were beveled 7° at one end to compensate for the bracket prescription, in order to align the load cell frame to the bracket frame that was centered on the slot. Dowels were coated on the beveled end surface with titanium oxide to enhance retention. After a thin layer of porcelain conditioner (Reliance) air dried, a thin layer of primer was added (OrthoSolo, Universal Bond Enhancer). With composite resin application (Transbond XT, 3M Unitek) to the bracket base, the bracket was positioned in the center of the dowel and light cured after removal of excess composite resin. Each bracket and dowel pair was numerically labeled.

3.2.3 Imaging the Bracket and Dowel Pair

The following procedure was used to precisely determine the location of the bracket on the dowel. This information was necessary to calculate the correct transformation from the load cell to the bracket coordinate system. The CCD camera (Bausch & Lomb) with 7x magnification captured 3 focused views (Figure 3-5) of each bracket and dowel pair. Free software for image processing called GNU Image Manipulation Program (GIMP) was downloaded (www.gimp.org).[22] A systematic technique was used with GIMP for each view to obtain the position and orientation of the coordinate system of the bracket slot center relative to the dowel center, also known as offset. For each bracket and dowel pair, the coordinate system of (x, y, z) displacement values and (θ, γ, β) angles were entered in the configuration file for the friction device. Directions were defined as follows: x axis along the wire direction, y axis coming out of the bracket, z axis along the bracket door, with θ rotating about y axis, γ rotating about x axis, and β rotating about z axis (Figure 3-6). To increase accuracy, each angle was measured twice and averaged. To calibrate the digital images, that is to determine the image scale in mm/pixel (approximately 0.005 mm/pixel), the diameter and height of each dowel was measured three times with a digital caliper and averaged. To measure intra-rater reliability, the same investigator repeated the imaging procedure from a random selection of 10 bracket and dowel pairs. Repeated imaging was completed after a week or more from the initial imaging to eliminate image recollection.

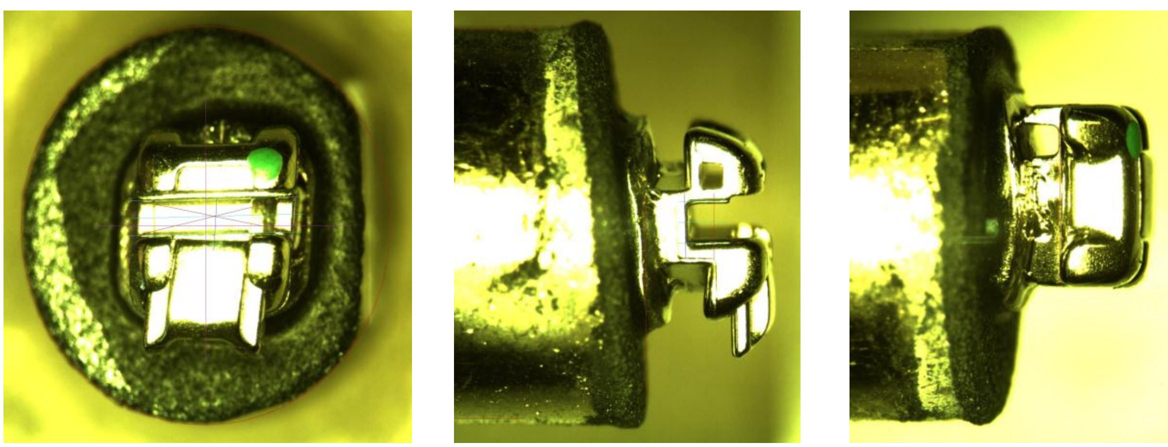

Figure 3-5. The 3 views of one bracket and dowel pair, with each view illustrating customized imaging from use of GIMP software.

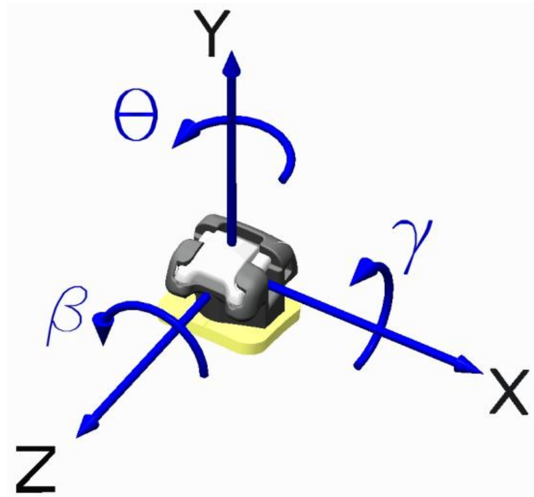

Figure 3-6. Illustration of x, y, z axis and θ, γ, and β angles.

3.2.4 The Testing Procedure

The 130 brackets were randomized to determine the order of bracket testing, with 65 brackets without and 65 brackets with elastomeric ligation (silver power O modules, size 0.120, Ormco, Orange CA), where each bracket was tested independently of one another. Brackets without elastomeric ligation represented a self-ligating bracket and brackets with elastomeric ligation represented a conventional bracket, while maintaining standardized bracket characteristics (bracket width and slot width) between groups. During initial testing, 2 brackets de-bonded from the dowel and 3 brackets de-bonded when the dowel diameter was trimmed to accommodate dowel insertion in the load cell adaptor. A thin layer of 5-minute epoxy (Adhaer) was placed on all bracket perimeters to increase retention. The θ were from 0° to 5°, recording every 0.5°, and returning from 5° to 0° (to assess hysteresis), recording every 1°, for a total of 16 angulations. For each angulation, the archwire moved 0.1mm at a rate of 0.1mm/sec with a data sampling rate of 2000 Hz and averaging 50 samples/channel (three channels each for force and moment). All brackets were coupled with 0.018 x 0.025" stainless steel archwire (Ormco, Orange CA) over 1.6mm distance. The angulations, wire selection, and rate were adapted from Robert Kusy's classic pioneering experiments.[23-26] Rectangular stainless steel wires were useful for sliding mechanics due to their lower coefficient of friction and surface roughness. Moreover, stainless steel bracket/stainless steel wire pairs remain the gold standard in dry and wet states.[3] To decrease contamination, 98% ethanol was used to cleanse each bracket and archwire, and nitrile gloves were used throughout testing procedure. A new archwire was installed for each bracket to avoid the introduction of wire distortions. A Straight Shooter Ligature Gun (TP Orthodontics) was used to standardize the force and stretching of elastomeric placement. A friction device protocol was followed for each test. A microscope was used to enhance visualization and ensure accuracy of the initial alignment of the archwire in the bracket slot. The log file included force and moment values in the x, y, and z directions, noted as Fx, Fy, Fz and Mx, My, Mz, respectively, for both the load cell and bracket. Noteworthy, force and moment data were collected only when the wire was translating.

After all brackets were tested in the dry state, the protocol was repeated and again randomized for the wet state, consisting of the one investigator's (MF) human saliva. A 200 microliter pipette (Pipetman) with sterile tips (Art Aerosol Resistant Tips) applied 50 microliter saliva, into bracket slot, before bracket door was closed and another 50 microliter saliva after bracket door was closed or elastomeric placed. This technique of dual saliva application was modified from Downing's protocol.[27] The wet tests were completed within 5 days from saliva collection, with saliva stored in a household freezer to preserve proteins.

3.2.5 Data Calculations

There were two levels of averaging. First, as stated previously, the DAQ collected data by averaging every 50 samples. Second, from the log file, all data with the same angulation was averaged over 0.1mm wire translation for each outcome: Fx, Fy, Fz, Mx, My, Mz experienced on the bracket. Therefore, each bracket had 16 values corresponding to each outcome for the dry state and 16 values corresponding to each outcome in the wet state. Two brackets (#57 and #91) were omitted due to severe data corruption during data acquisition. A total of 123 brackets resulted corresponding to 63 with no elastomeric ligation and 60 with elastomeric ligation. Therefore, the sample size for each group was nearly equal.

3.2.6 Statistical Analysis

Intra-class correlation coefficient (ICC) was used to assess intra-rater reliability. Repeated measures multivariate analysis of variance (MANOVA) was used to evaluate the main effects, pairwise interactions, and three-way interactions among ligation method, state, and angulation. Statistically significant main effects were further considered by pairwise comparisons to detect intra-group differences. The level of significance for all tests was set at alpha=0.05 (Statistical Package for Social Sciences or SPSS, Version 19).

3.3 Results

ICC values above 0.7 were considered fair, 0.8 were considered good, and excellent if above 0.9 (Table 3-1), with the latter two corresponding to high reliability. The primary investigator's ICC ranged from 0.93 to 0.99 for all variables, except 0.72 for γ. The load cell transformation of θ, γ, and β included cosine and sine functions. As these angles averaged 1° or less, the cosine and sine of these angles would be near one and zero, respectively. Errors in the measurement of these angles (less than 1°) therefore had little effect on a bracket's calculated force and moment values. As the ICC was excellent for displacement, the principal measurement, the overall intra-rater reliability of this study was very high. To introduce inter-rater reliability and compare with intra-rater reliability, refer to Appendix B.

Table 3-1. The intra-class correlation coefficient (ICC) of primary investigator to assess intra-rater reliability (n=10).

Investigator	ICC Displacement			ICC Angle		
	x	y	z	θ	γ	β
MF	0.99 (0.97, 1.0)	0.98 (0.94, 1.0)	0.98 (0.91, 0.99)	0.98 (0.86, 1.0)	0.72* (0.31, 0.92)	0.93 (0.82, 0.98)

The upper and lower bound of 95% confidence interval (CI) are noted within the parenthesis.
*Correspond to ICC values below 0.8.

The potential errors of the testing apparatus were quantified for the load cell and transformation from the load cell frame to the bracket frame. With a 16-bit DAQ system, the resolution for the load cell was 0.003 N for force and 0.008 Nmm for moment. With three times the average standard deviation and worst case offsets, the overall transformation error was less than 0.8% for Fx, Fz, and My, our most interested outcomes, and between 1.9-2.8% for Fy, Mx, and Mz. In general, these marginal errors of our friction device apparatus were acceptable.

With this experimental design, the distance an archwire was translated correlated highly with the angulation of the bracket. Since the effect of angulation was a primary objective for this study and its value well documented in the literature, distance was thereby not analyzed. Although this device was equipped with a variable interbracket distance, testing occurred in the middle of the wire and with as small of a wire translation as possible to minimize the change in effective stiffness of the wire. Specifically, distance of wire translation was reduced to minimize its overall effect on wire stiffness, such that a 1mm distance was set from 0° to 5° and 0.6mm distance returning from 5° to 0°.

The critical contact angle for binding (θ_c) refers to the angulation at which the archwire first contacts the edges of the slot walls.[26] As sliding is ideal when $\theta \approx \theta_c$,[9] acknowledging θ_c for a specific bracket-archwire combination is essential to enhancing sliding, specifically by only initiating sliding mechanics when near θ_c. For the Damon Q self-ligating bracket and 0.018 x 0.025" archwire used in this study, the approximate theoretical θ_c is 2.08° with values of 0.018" for size, 0.022" for slot, and 0.110" for width from experimental parameters. For this equation[8] and calculation specifics refer to Appendix C.

The overall relationships between force and angulation, as well as moment and angulation, specific for each direction (x, y, z), state (dry/wet), and ligation method (no elastomeric ligation/elastomeric ligation) are illustrated in Figures 3-7 to 3-12. General trends were further described, noting that a negative sign of force and moment refers to direction in the bracket frame.

For Figure 3-7A self-ligating bracket in both states, a change from zero Fx to a linear increase was evident after 2.5°. As θ decreased, Fx decreased in a similar linear fashion with no hysteresis. For Figure 3-7B conventional bracket in the dry state, Fx was near 1 N at 0° and steadily increased to four times the value of self-ligating bracket. As θ decreased, Fx remained at the peak level. The wet state was analogous to the dry state.

For Figure 3-8A self-ligating bracket in both states, a near zero Fy was shown as θ increased and decreased, with no hysteresis. For Figure 3-8B conventional bracket in the dry state, a similar near zero Fy was evident with a small increase in magnitude above 4.0° and mild hysteresis. The wet state was similar to the dry state, although the increase in Fy magnitude occurred above 2.0°.

For Figure 3-9A self-ligating bracket in both states, change from zero Fz to a linear increase in magnitude was shown after 2.0°. As θ decreased, Fz decreased in magnitude in a similar linear fashion with no hysteresis. For Figure 3-9B conventional bracket in both states, Fz also changed from zero to a linear increase in magnitude after 2.0°, although with mild evidence of hysteresis.

For Figure 3-10A self-ligating bracket in both states, a small change from zero Mx to linear increase in magnitude was shown after 2.5°. As θ decreased, Mx decreased in magnitude in a similar linear pattern with no hysteresis. For

Figure 3-10B conventional bracket in both states, Mx followed a similar trend to self-ligating bracket including overall magnitude.

For Figure 3-11A self-ligating bracket in both states, a change from zero My to linear increase was evident after 2.0° (i.e. the critical angle for binding). As θ decreased, My decreased in a similar linear pattern with no hysteresis. For Figure 3-11B conventional bracket in both states, a gradual change from zero My to a linear increase was evident after 2.0°, with larger magnitudes than self-ligating bracket. Comparable to self-ligating bracket, as θ decreased My decreased in a similar linear pattern with no hysteresis.

For Figure 3-12A self-ligating bracket in both states, a change from zero Mz to a linear increase in magnitude was shown after 2.0°. As θ decreased, Mz decreased in magnitude in a similar linear fashion with no hysteresis. For Figure 3-12B conventional bracket in both states, Mz was near 5 Nmm at 0°and steadily increased in magnitude to nearly three times the self-ligating bracket value, with dry state having larger magnitude. As θ decreased, Mz remained at an increased magnitude.

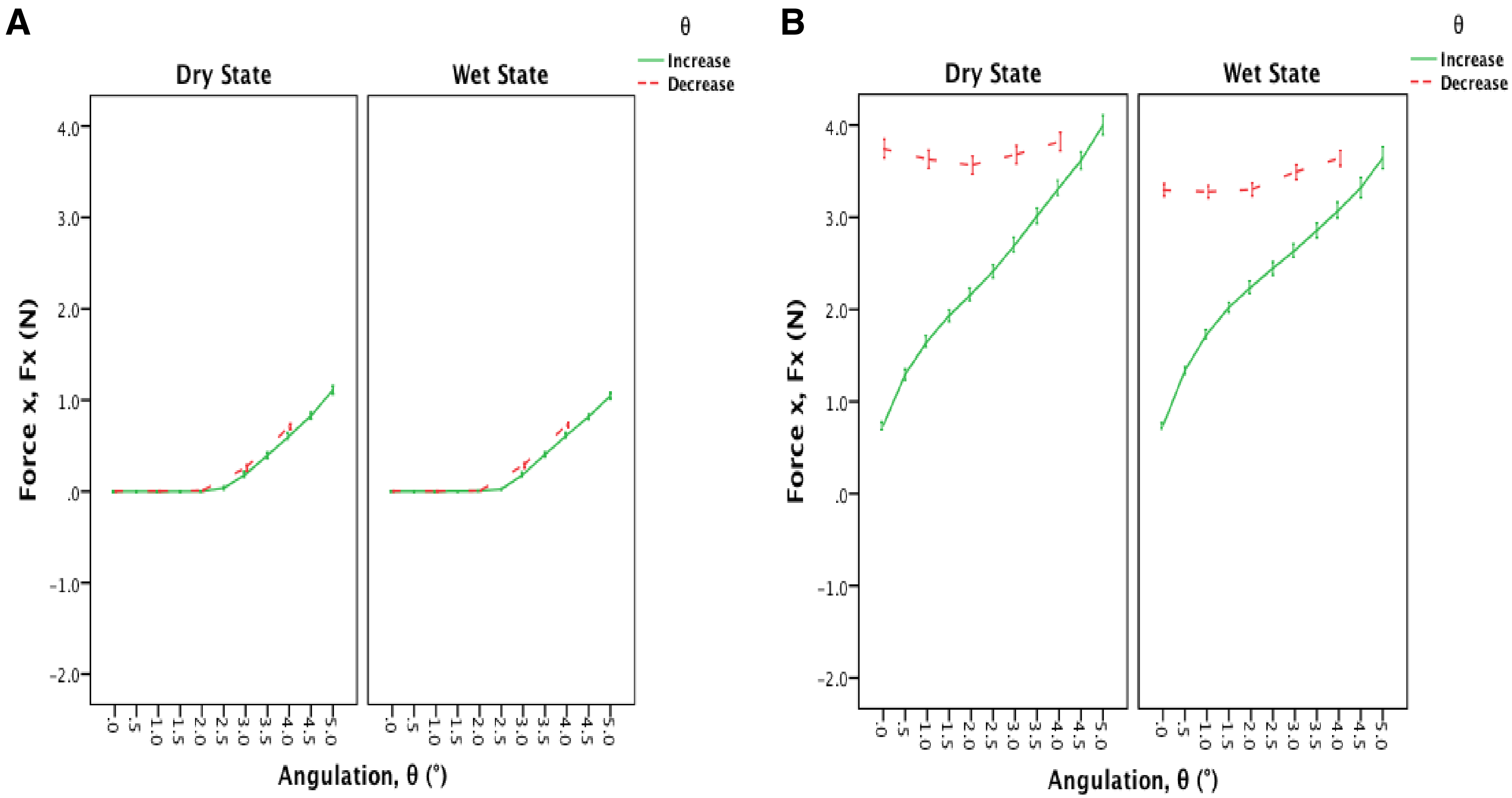

Figure 3-7. **A,** Fx as a function of θ for no elastomeric ligation (self-ligating bracket) in dry and wet states. **B,** Fx as a function of θ for elastomeric ligation (conventional bracket) in dry and wet states. **A and B,** Error bars (95% CI) are displayed.

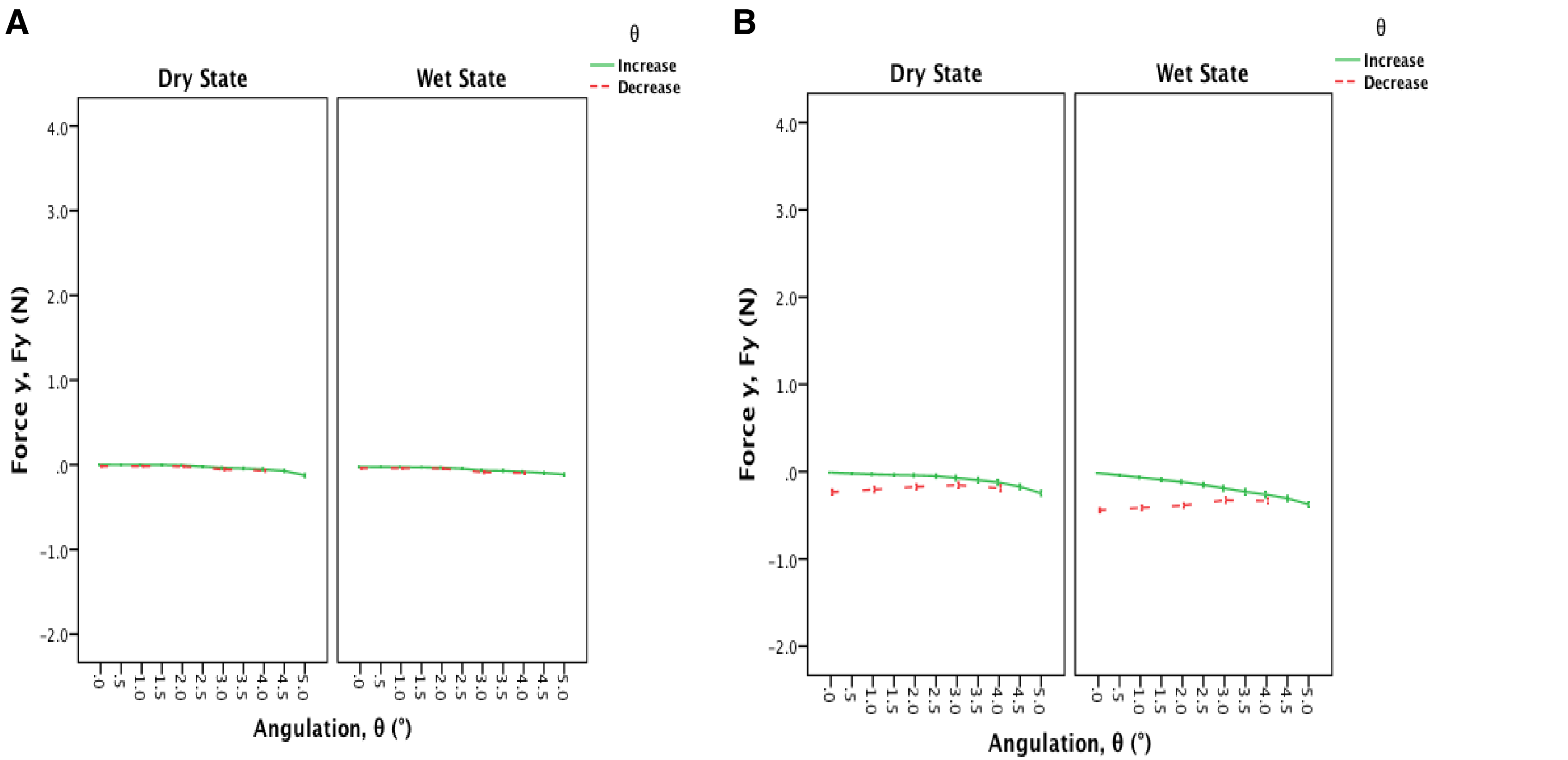

Figure 3-8. **A,** Fy as a function of θ for no elastomeric ligation (self-ligating bracket) in dry and wet states. **B,** Fy as a function of θ for elastomeric ligation (conventional bracket) in dry and wet states. **A and B,** Error bars (95% CI) are displayed.

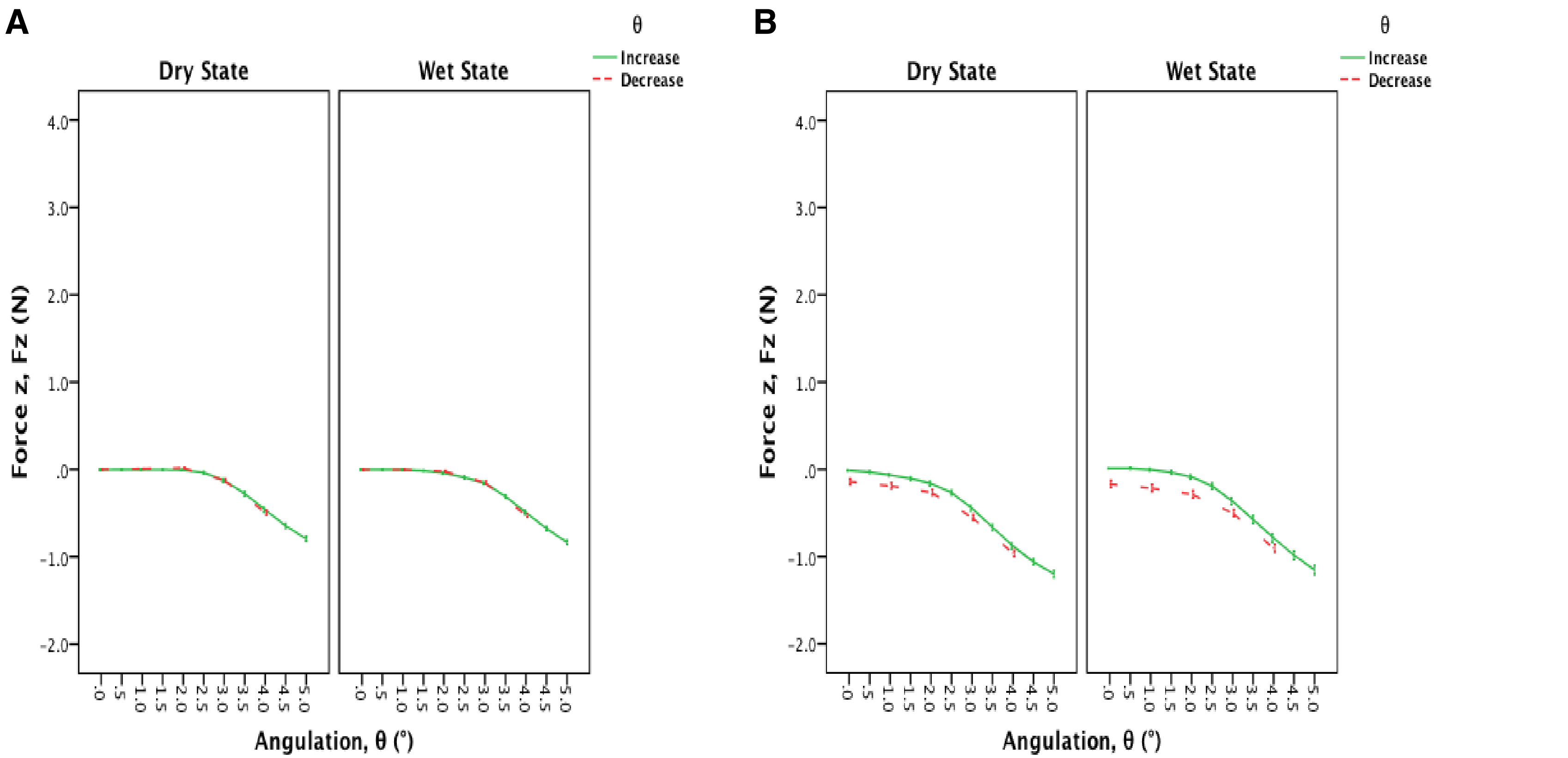

Figure 3-9. **A,** Fz as a function of θ for no elastomeric ligation (self-ligating bracket) in dry and wet states. **B,** Fz as a function of θ for elastomeric ligation (conventional bracket) in dry and wet states. **A and B,** Error bars (95% CI) are displayed.

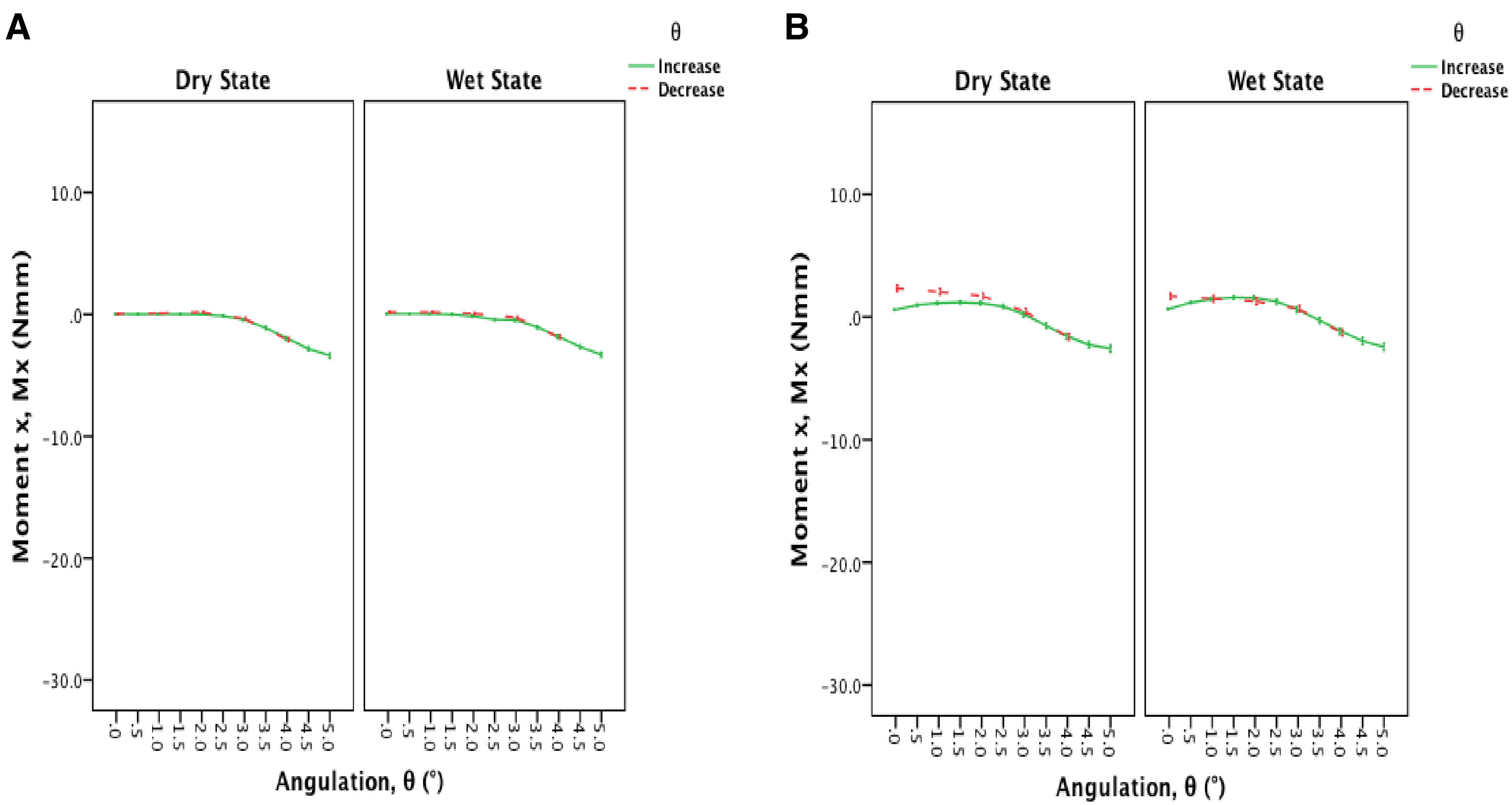

Figure 3-10. **A,** Mx as a function of θ for no elastomeric ligation (self-ligating bracket) in dry and wet states. **B,** Mx as a function of θ for elastomeric ligation (conventional bracket) in dry and wet states. **A and B,** Error bars (95% CI) are displayed.

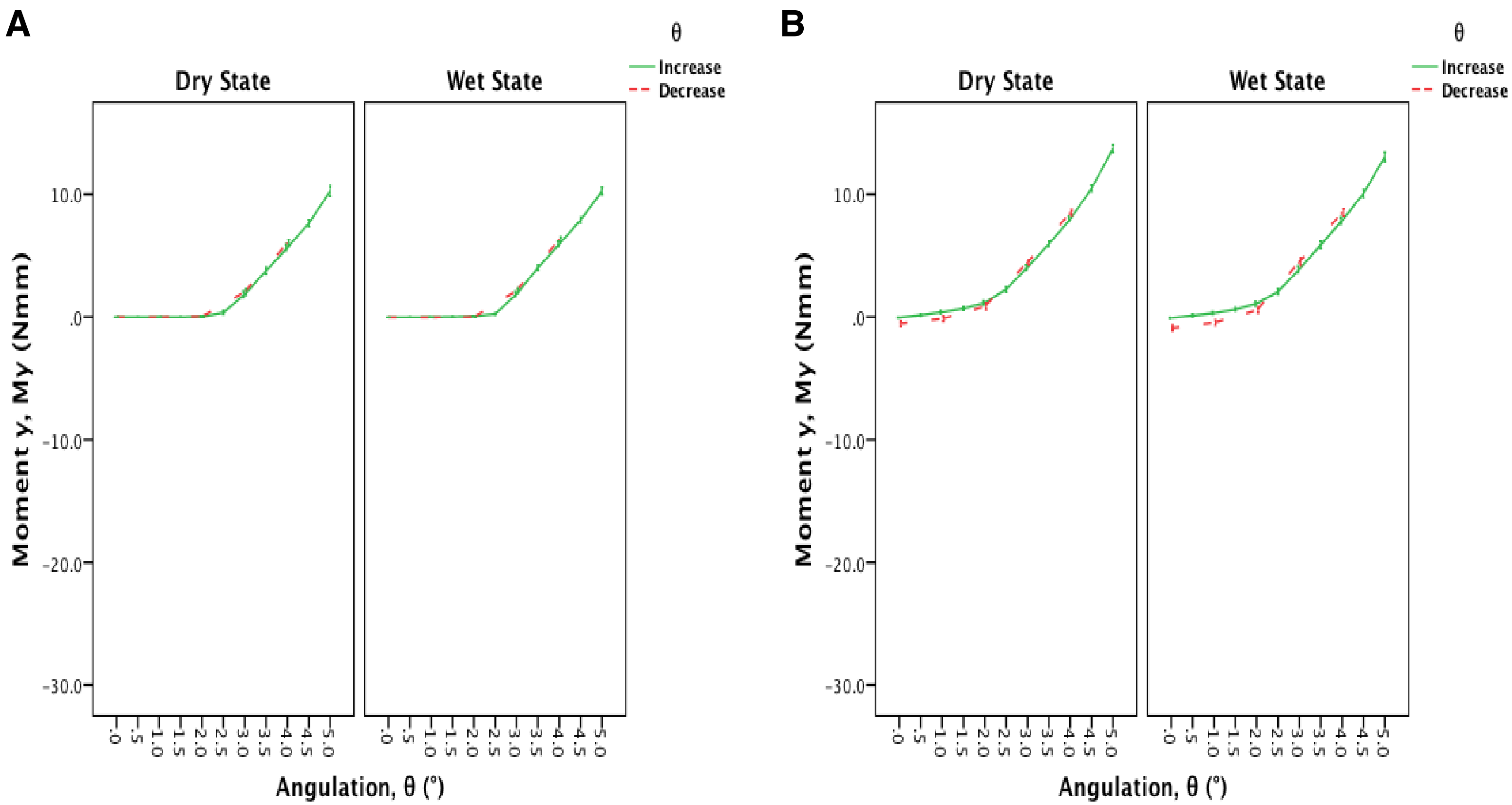

Figure 3-11. **A,** My as a function of θ for no elastomeric ligation (self-ligating bracket) in dry and wet states. **B,** My as a function of θ for elastomeric ligation (conventional bracket) in dry and wet states. **A and B,** Error bars (95% CI) are displayed.

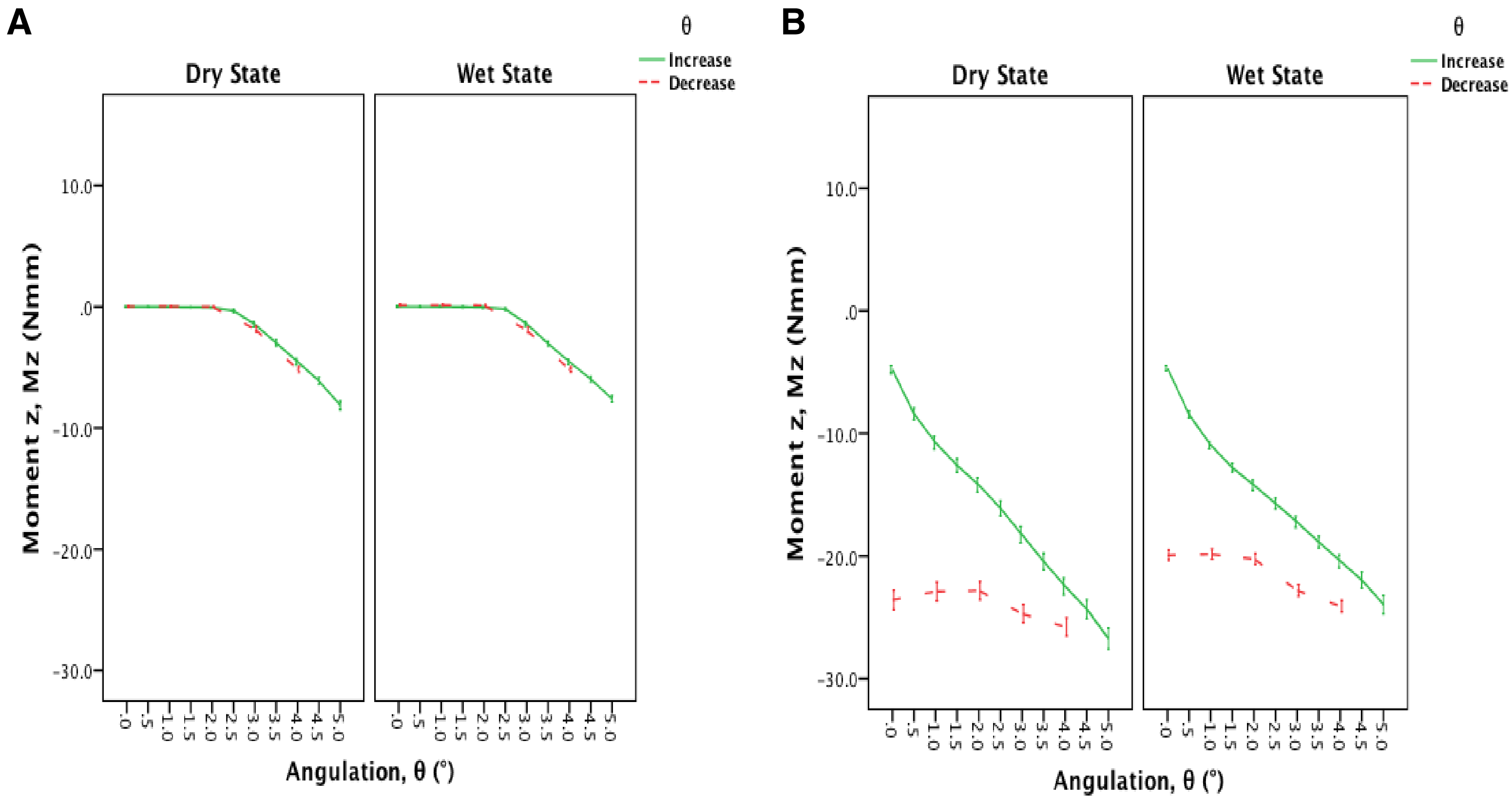

Figure 3-12. **A,** Mz as a function of θ for no elastomeric ligation (self-ligating bracket) in dry and wet states. **B,** Mz as a function of θ for elastomeric ligation (conventional bracket) in dry and wet states. **A and B,** Error bars (95% CI) are displayed.

With only Fx analyzed by previous researchers and the role of binding illustrated by My, the major factors of this study were clearly Fx and My. Further analysis of Fx and My at initial 0° and 5° angulations for both states and ligation methods was pursued to determine the main effects and dominant influences. The boxplots summarizing Fx (Figure 3-13) and My (Figure 3-14) illustrate normality, although outlier data points were evident. Furthermore, the box plots do not illustrate equal variance. Refer to Appendix D for boxplots of Fy, Fz, Mx, and Mz.

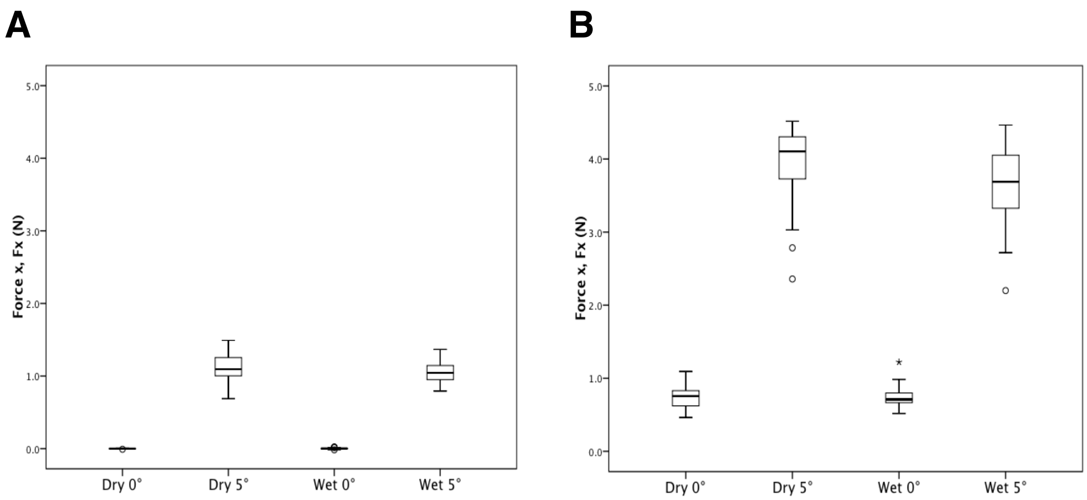

Figure 3-13. **A,** Boxplot of Fx, with no elastomeric ligation (self-ligating bracket), for dry and wet states at 0° and 5°. **B,** Boxplot of Fx, with elastomeric ligation (conventional bracket), for dry and wet states at 0° and 5°.

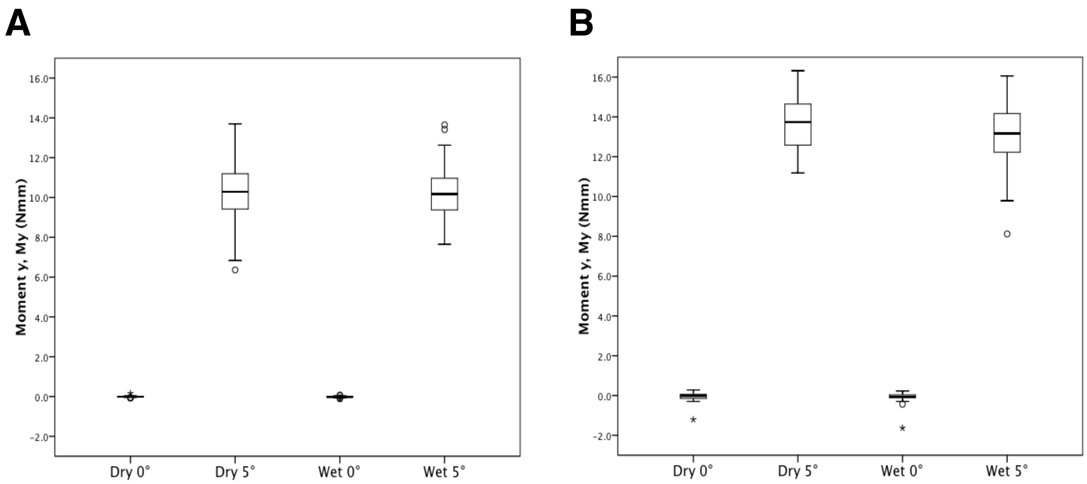

Figure 3-14. **A,** Boxplot of My, with no elastomeric ligation (self-ligating bracket), for dry and wet states at 0° and 5°. **B,** Boxplot of My, with elastomeric ligation (conventional bracket), for dry and wet states at 0° and 5°.

Repeated measures MANOVA of Fx, Fy, Fz, Mx, My, and Mz found significant multivariate effects (Table 3-2) for the main effects of elastomer, state, angulation, and all interactions. Large effect size was seen for elastomer, angulation, and interaction of angulation and elastomer, such that 98%, 100%, and 96% of the variability in the dependent variables could be accounted for by elastomer, angulation, and interaction of angulation and elastomer, respectively. Univariate analysis (Table 3-3) were significant for all outcomes except for My of state and elastomer interaction, My of state and angulation interaction, and My of three-way interaction. For Fx 98%, 99%, and 95% of variability was explained for by elastomer, angulation, and interaction of angulation and elastomer, respectively. For My 99% of variability was accounted for by only angulation. Refer to Appendix E for the univariate analysis of Fy, Fz, Mx, and Mz.

Table 3-2. Multivariate analysis for repeated measures MANOVA of Fx, Fy, Fz, Mx, My, and Mz (n=123).

Multivariate Main Effects	F	*P*	η_p^2
Elastomer	986.1	<0.001*	0.98
State	12.8	<0.001*	0.40
State + Elastomer	7.6	<0.001*	0.28
Angulation	3587.0	<0.001*	1.00
Angulation + Elastomer	423.2	<0.001*	0.96
State + Angulation	13.1	<0.001*	0.40
State + Angulation + Elastomer	12.6	<0.001*	0.40

F=F statistic, $P \leq 0.05$ was significant (denoted *), η_p^2 = Partial Eta Squared.
Degrees of freedom (6, 116) for each effect.

Table 3-3. Univariate analysis (n=123).

Effects	Outcome	F	*P*	η_p^2
Elastomer	Fx	5793.7	<0.001*	0.98
	My	246.0	<0.001*	0.67
State	Fx	19.3	<0.001*	0.14
	My	4.3	0.040*	0.03
State + Elastomer	Fx	9.5	0.003*	0.07
	My	3.8	0.053	0.03
Angulation	Fx	9632.8	<0.001*	0.99
	My	17590.8	<0.001*	0.99
Angulation + Elastomer	Fx	2237.0	<0.001*	0.95
	My	314.1	<0.001*	0.72
State + Angulation	Fx	25.4	<0.001*	0.17
	My	3.5	0.064	0.03
State + Angulation +	Fx	11.9	0.001*	0.09
Elastomer	My	3.6	0.060	0.03

F=F statistic, $P \leq 0.05$ was significant (denoted *), η_p^2 = Partial Eta Squared.
Degrees of freedom (1, 121) for each effect.

To investigate and quantify the dominant influences on Fx and My, specific repeated measures ANOVA was completed with pairwise comparisons (Table 3-4). Refer to Appendix F for mean and standard deviations specific to each outcome. For Fx at 0°, elastomer was significant, where 96% of variability was explained, with a mean difference of 0.74 N for elastomeric ligation. For Fx at 5°, both state and elastomer were significant. For state, 16% of variability was accounted for with a mean difference of 0.21 N for dry state. For elastomer, 97%

of variability was explained with a mean difference of 2.74 N for elastomeric ligation. For My at 0°, elastomer was weakly significant with only 3% of variability accounted for with a mean difference of -0.05 Nmm for elastomeric ligation. For My at 5°, elastomer was significant and state was weakly significant. For elastomer, 70% of variability was explained with a mean difference of 3.12 Nmm for elastomeric ligation. For state, 3% of variability was accounted for with a mean difference of 0.33 Nmm for dry state. The interaction of state and elastomer was significant for only Fx at 5°, with a mean difference of 0.30 N. Overall, the ligation method versus state was the most important factor for Fx and My, although at varying levels depending on the angulation. Generally, an elastomeric (conventional bracket) increased Fx and My compared to no elastomeric ligation (self-ligating bracket). Refer to Appendix G for profile plots of the interaction of state and elastomer.

Table 3-4. Repeated measures ANOVA for each outcome and mean differences from pairwise comparisons (n=123).

Outcome	Effects	F	*P*	η_p^2	Mean Difference**
Fx 0°	State	0.001	0.982	4.0×10^{-6}	NS
	State +Elastomer	0.033	0.856	2.7×10^{-4}	NS
	Elastomer	2904.2	<0.001*	0.96	0.74 N
Fx 5°	State	23.6	<0.001*	0.16	0.21 N
	State +Elastomer	11.3	0.001*	0.09	0.30 N
	Elastomer	4281.9	<0.001*	0.97	2.74 N
My 0°	State	2.3	0.134	0.02	NS
	State +Elastomer	0.2	0.685	0.001	NS
	Elastomer	4.0	0.047*	0.03	-0.05 Nmm
My 5°	State	3.9	0.050*	0.03	0.33 Nmm
	State +Elastomer	3.7	0.056	0.03	NS
	Elastomer	282.3	<0.001*	0.70	3.12 Nmm

F=F statistic, $P \leq 0.05$ was significant (denoted *), η_p^2 = Partial Eta Squared.
**If *P* significant, mean differences recorded from pairwise comparisons for State (Dry – Wet), Elastomer (Yes – No), and interaction of State + Elastomer.
NS = Not significant.
Degrees of freedom (1, 121) for each effect.

Analyzing the relationship between My as a function of Fx would be valuable in order to determine the coefficient of kinetic friction in this study with 0.018 x 0.025" stainless steel archwire. At angulation above the critical contact angle for binding (2°), Figure 3-15 illustrates My to be a linear function of Fx for both ligation methods. An analytical model for the effect of angulation on Fx was established.[28] An equation for the linear relationship between My and Fx, where w refers to bracket width and μ refers to the coefficient of friction, can be expressed as:[28]

$$My = \frac{w}{2\mu} Fx$$

With the slope of Figure 3-15 representing $\frac{w}{2\mu}$ and w of Damon Q self-ligating bracket was 2.794 mm, μ was calculated to be approximately 0.16 for no elastomeric ligation (self-ligating bracket) and approximately 0.19 for elastomeric ligation (conventional bracket).[28]

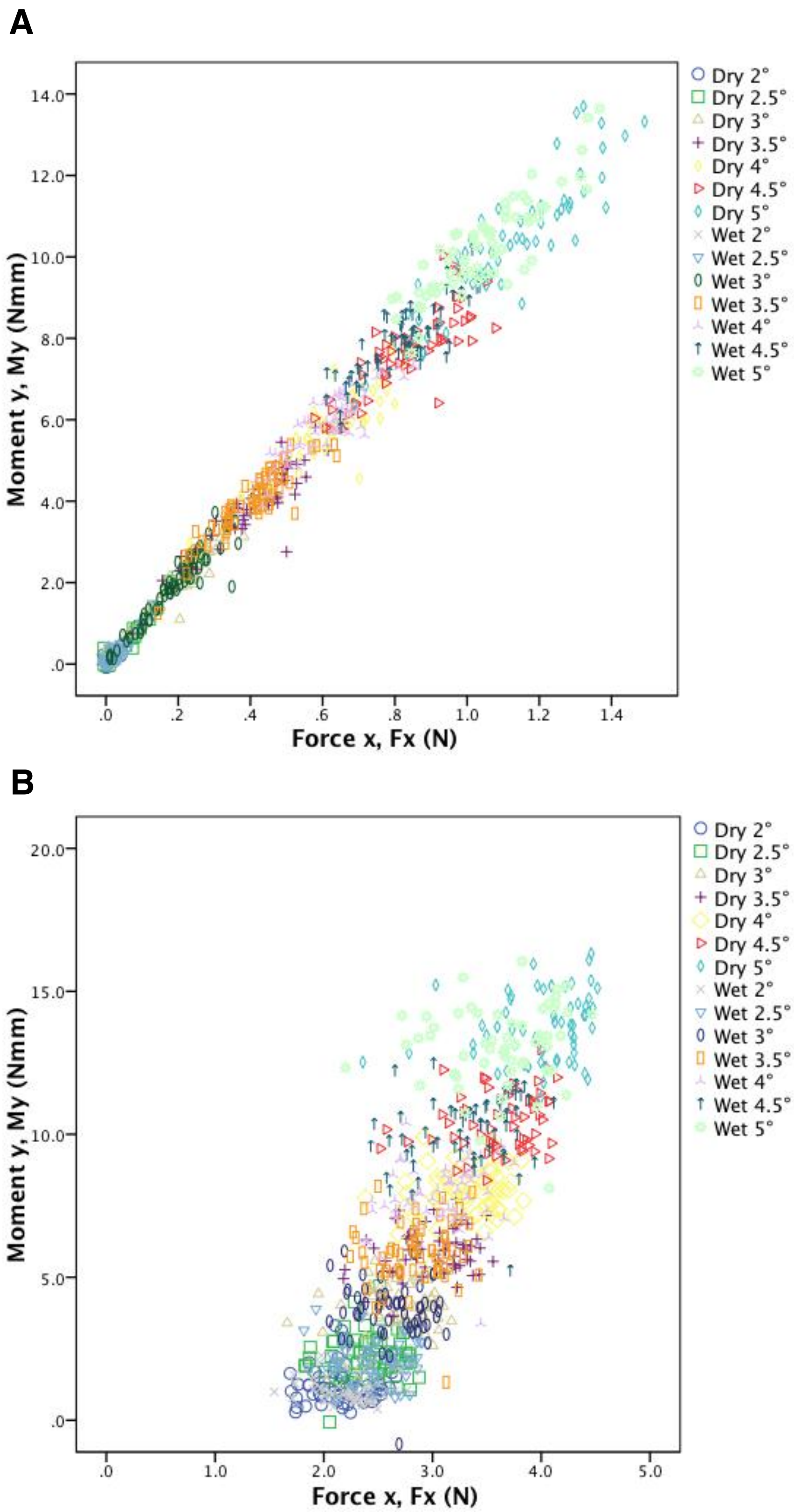

Figure 3-15. My as a function of Fx for both states. **A,** No elastomeric ligation (self-ligating bracket) from 2° to 5°. **B,** Elastomeric ligation (conventional bracket) from 2° to 5°.

3.4 Discussion

Since friction is a force tangent to the plane of contact, Fx can be labeled the frictional force or simply friction. Conversely, Fy and Fz are termed the normal forces. Previous studies assessed friction in 1D, where solely Fx was measured and with binding, resistance to sliding was evaluated. With angulation, both Fx and Fz are components of resistance to sliding in the direction of the wire. To reflect the total resistance to sliding, the Fz component should be quantified and studied, in addition to the Fx component. The 3D friction device evaluates Fx, Fy, Fz, Mx, My, and Mz, where measurements of Fy, Fz, Mx, My, and Mz are unique to this study. My is related to the forces in the XZ plane and with the coefficient of friction, My is related to Fx and Fz. To explore friction and resistance to sliding, the most appealing outcomes are indeed Fx, Fz, and My.

Thorstenson and Kusy[24-26,29] outlined their Fx conclusions based on θ_c. To summarize for self-ligating bracket when $\theta < \theta c$, the values of resistance to sliding appeared little or zero, were independent of angulation, and the slopes varied about zero, and when $\theta \geq \theta_c$, resistance to sliding linearly increased as angulation increased.[24-26] Furthermore for self-ligating bracket when $\theta \geq \theta_c$, both friction and binding contributed to resistance to sliding, where friction depended only on the ligation force, not on angulation, and binding, on the other hand, depended on angulation.[26] For conventional bracket when $\theta < \theta_c$, the values of resistance to sliding appeared constant, although greater than self-ligating bracket due to the frictional component, yet still independent of angulation.[26,29] For conventional bracket when $\theta \geq \theta_c$, like self-ligating bracket, resistance to sliding linearly increased as angulation increased.[26,29]

For this study, Figures 3-7 to 3-12, which illustrated small error bars, were each reviewed to assess comparisons between the self-ligating bracket and the conventional bracket. For Fx of self-ligating bracket, the trend agreed with Thorstenson and Kusy, where frictional force was zero when $\theta < \theta_c$ and linearly increased when $\theta \geq \theta_c$. However, Fx of conventional bracket did not illustrate Thorstenson and Kusy's result of an additive effect of frictional force when $\theta < \theta_c$ and a linear increase when $\theta \geq \theta_c$. In fact, Fx of conventional bracket showed a linear increase of frictional force from initial angulation of 0° and was approximately four times greater than self-ligating bracket. This difference may be attributed to our experimental setup. The distance of wire translation per angulation was 0.1mm in this study compared to the longer wire translation of 1.25mm to 2.5mm for Kusy's studies.[24-26] Due to our short distance, the elastomer likely could not rebound and a linear increase in Fx occurred. With a longer distance, the elastomer could rebound and therefore reduce Fx, specifically to a constant value if $\theta < \theta_c$.

For Fy, both self-ligating bracket and conventional bracket were near zero forces, although conventional bracket had slightly increased force magnitude. The latter was likely due to additional force during binding from the elastomer to the bracket-wire interface. For both self-ligating bracket and conventional bracket of Fz, the force was zero when $\theta < \theta_c$ and increased linearly in magnitude when $\theta \geq \theta_c$, similar to Fx of self-ligating bracket. However, the self-ligating bracket had slightly more Fz magnitude than the conventional bracket. Since Fx and Fz both lie in the XZ plane and are perpendicular to the bracket rotation direction, the similar shapes of Fx and Fz illustrate that they are in fact related. Furthermore, Fx and Fz are the components of resistance to sliding.

Comparable to Fx self-ligating bracket and Fz, Mx had a similar trend for both self-ligating bracket and conventional bracket, although the same moment magnitude. Although a smaller magnitude compared to My and Mz, Mx was likely due to rotational misalignment of the wire, especially during binding, from the wire clamp design of the friction device. For My, the self-ligating bracket replicated Fx self-ligating bracket and on the other hand, conventional bracket had a more gradual change around θ_c and an increased magnitude than the self-ligating bracket. Overall, the My graphs correlated highly with the shapes of the Fx and Fz graphs, as expected, since they are related. For Mz, the self-ligating bracket illustrated zero moment when $\theta < \theta_c$ and increased linearly in magnitude when $\theta \geq \theta_c$, whereas the conventional bracket showed a linear increase in moment from initial angulation of 0° and was nearly three times greater than self-ligating bracket. Mz could perhaps arise from lateral wire movement due to the wire clamp design.

To further compare Figures 3-7 to 3-12, a marked difference between self-ligating bracket and conventional bracket was evident for both Fx and Mz. The main cause for these differences was the application of an elastomer. As stated previously, the lack of an elastomer rebound over a short distance may cause the linear increase in Fx. Variability within elastomers may also exist, where the tension of each elastomer may be dissimilar even though new elastomers were tested. During data collection, large variance between elastomers was not evident. Theoretically, Fx and Mz could arise by a z-offset error in the transformation from the load cell frame to bracket frame. Moreover, while the My trend was anticipated, the outcomes of Mx and especially Mz were surprisingly not zero because of potential wire rotation or movement. Future studies with a more secure wire clamp design would be recommended to provide insight into these moment effects. This information would be valuable to determine the true moment effects without design shortcomings.

The main effects of this study illustrated that angulation, elastomer, and the interaction of angulation and elastomer primarily influenced all outcomes. As angulation increased, the magnitudes of Fx for conventional bracket and Mz for conventional bracket increased linearly, whereas the magnitudes of Fx for self-ligating bracket, Fz, Mx, My, and Mz for self-ligating bracket increased after binding. Past studies were in agreement that frictional force (Fx) increased as angulation increased. The ligation method played a significant role in this study, where generally self-ligating bracket had less Fx and My compared to conventional bracket. Noteworthy, no consistent pattern existed for the frictional forces of conventional elastomers in the published literature.

Lastly, state was only significant for Fx at 5° and weakly significant for My at 5°, with human saliva acting as a lubricant for both. There was no effect from state at 0° for both Fx and My. Overall, saliva's role of little effect or lubricious behavior on frictional force was comparable to past research of a complex pattern for saliva to increase, decrease, or not alter frictional force.

The coefficient of kinetic friction for self-ligating bracket in this study was 0.16, which is similar to 0.14 reported by Thorstenson and Kusy.[24] Other than Thorstenson and Kusy,[24] only our paper reported the coefficient of kinetic friction for self-ligating bracket at the present time. The coefficient of kinetic friction for conventional bracket by Leander and Kumar[30] at 0.27 was greater than 0.19 reported here because of their inclusion of the direct friction caused by the elastomer. Future research studying the coefficients of kinetic friction, especially for conventional bracket, would be valuable for comparison to our 3D friction device.

It is important to acknowledge the methodological differences between studies, which make direct comparisons of the published studies complex and could explain inconsistent results.[27] In comparison to other frictional studies, the strengths of this study included a large and justified sample size, marginal error in our friction device (reported earlier), high intra-rater reliability, testing a range of angulation in dry and wet states, reporting θ_c, utilizing standard techniques for CEL placement and saliva application, and no confounding variables of elastomers, brackets, wires, or investigators. Although a rare observation in the literature, the application of a CEL on a self-ligating bracket to represent a conventional bracket is highly recommended to standardize the bracket material, slot dimension, and bracket width, thereby eliminating potential confounding study variables.

3.4.1 Clinical Significance

Results should be interpreted with caution when applying to clinical situations, as in-vitro studies cannot replicate all the factors that affect the resistance to sliding that may occur in-vivo.[6] Laboratory findings, therefore, are a guide to the expected clinical performance.[21] Noteworthy, only four of the 21 variables contributing to friction between a bracket and an archwire were evaluated,[5] illustrating an over-simplified model. A force of 0.5 N or 50 g is generally accepted as being clinically significant. With no published literature on moment experienced by a bracket, clinically significant values are unknown. A moment of 1 Nmm could be viewed as being clinically significant, where unwanted tooth movement prevailed. Elastomeric ligation for Fx was clinically significant at 0.74 N for 0° and 2.74 N for 5°, whereas state and interaction of state and elastomer were not clinically significant. Similarly, elastomeric ligation for My was clinically significant at 3.12 Nmm for only 5°. All other My effects were not significant, except My at 0° for elastomer and My at 5° for state were both weakly significant. Overall, the ligation method was the dominant factor, with the mean difference more pronounced at higher angulations. Specifically, the finding that conventional bracket had higher Fx and My compared to self-ligating bracket may influence a clinician's choice of bracket selection when customizing a patient's treatment plan. Hopefully future research investigating numerous frictional force variables can establish whether self-ligating bracket are superior clinically or not.

Interestingly, friction may be overstated in its importance in orthodontic appliances.[31] Intra-oral masticatory forces promoting tooth mobility and biological factors affect the resistance to sliding at the bracket-archwire interface.[32] Indeed, friction may be overcome from these tooth movements and from the elasticity of the periodontal ligament.[19] In fact, frictional forces in-vivo are less than in steady state experiments,[31,33] as no ideal force absorbing mechanisms exist in-vitro.[34] Furthermore, oscillation of a bracket, as little as 0.16 mm of mesiodistal crown movement, could reduce resistance to sliding by 85%.[35] With elastomers, areas of binding or notching may be temporarily relieved with occlusal forces, although unlikely for the ligation force to be reduced simultaneously at multiple interfaces.[36] Overall, physiological functions could significantly decrease or even eliminate resistance to sliding.[37] The fascination of studying frictional resistance may be overestimated.

3.4.2 Limitations

Inter-bracket distance has an effect on resistance to sliding due to a change in effective stiffness of the wire. The requirement to use small wire translation increments in order to stay in the middle of the wire is a limitation of the current system, which potentially had an effect on the results with elastomers. Although variation in this distance was reduced to minimize this effect, a constant inter-bracket distance would be the ideal and recommended for the next generation 3D friction device. While the GIMP software for imaging was reliable and reproducible, the time consuming nature (i.e. 30-40 minutes for each bracket and dowel pair) was a drawback. For studies with a large sample size, an imaging program with similar advantages and decrease in time commitment would be an asset to the investigators. A translucent dowel would ensure curing of the composite resin under the bracket and eliminate both the need and time for surface epoxy application. A more secure wire clamp design would ensure no rotational or lateral wire movements contributing to moment effects. Ideally, human saliva should be stored in -80°C freezer if conducting tests over a long period of time, to halt the denaturation process of proteins and maintain the original integrity of saliva.

As quantified earlier, the minimal errors from the friction device were acceptable. Although manufacturing variations of brackets and wires exist, they are generally unknown to the clinician. To illustrate variability from the theoretical θ_c of 2.08° in this study, manufacturing tolerance errors of 0.0005" for archwire width, 0.0005" for slot width, and 0.002" for bracket width could produce θ_c from 1.54° to 2.65°. This range of 1.11° in critical contact angle for binding can contribute to the variability in results. In this study, the variations in measured data are more likely to arise from bracket and wire geometry variations than from errors in the friction apparatus. With no standards for orthodontic materials, manufacturers are self-controlled. This is a major disadvantage to clinicians and should be re-evaluated.

This novel device measured kinetic friction on an isolated bracket in a steady state environment. Though clinical conditions are complicated to simulate in-vitro,[27] future studies evaluating both static and kinetic friction on a segment of brackets experiencing oral functions, such as vibrations or vertical displacements, would be insightful.

3.5 Conclusion

1. Mean force and moment were significantly different between elastomeric and no elastomeric ligation.
2. Mean force and moment were significantly different between dry and wet state.
3. Mean force and moment were significantly different between 0° and 5° angulation.
4. At 0° angulation, elastomeric ligation was significantly greater by 0.74 N compared to no elastomeric ligation; no elastomeric ligation was weakly significantly greater by 0.05 Nmm compared to elastomeric ligation. At 5° angulation, elastomeric ligation was significantly greater by 2.74 N and 3.12 Nmm compared to no elastomeric ligation.
5. At 0° angulation, there was no difference in mean force and moment between dry and wet state. At 5° angulation, dry state was significantly greater by 0.21 N and weakly significantly greater by 0.33 Nmm compared to wet state.
6. Similar to Robert Kusy's work for Fx, θ_c was noted experimentally, where friction dominated below θ_c and binding dominated above θ_c.
7. The experimental θ_c value agreed with the theoretical θ_c equation based on bracket and wire geometry.

8. Similar to Robert Kusy's work for Fx, above θ_c resistance to sliding increased linearly with angulation.
9. Dissimilar to Robert Kusy's work for Fx, elastomeric ligation did not superimpose a constant offset of the resistance to sliding to angulation curve.

There was strong evidence for Fx and My on the Damon Q self-ligating bracket to be significantly influenced by the effects of second-order angulation, elastomer, state, and most interactions. Specifically, the dominant influences for Fx were second-order angulation, elastomer, and the interaction of angulation and elastomer, while second-order angulation primarily influenced My. As second-order angulation increased, the magnitudes of Fx and My also increased. For ligation method, self-ligating bracket had less Fx and My compared to conventional bracket.

The novelty of this 3D friction device includes measuring forces and moments in the x, y, and z directions at the bracket, not archwire, level. These unique properties, in addition to the marginal data errors, strengthen the utilization of this 3D device. Indeed, 3D technology should be the standard protocol for understanding the friction phenomenon, as current 1D methods are limited in scope of information and application to in-vivo situations.

The methodological variability between research teams makes comparisons between studies difficult or nearly impossible. As the interest in friction for orthodontic tooth movement continues to soar, a goal of the profession should entail more standardized testing methods. This may include collaboration between research groups to use the same device and/or protocol and thereby enhance our knowledge base of friction and make more sound conclusions.

Acknowledgement

I would like to thank Ormco for the generous donation of brackets and archwires tested in this investigation and Mr. Garrett Melenka for his technical assistance in using the 3D friction device.

3.6 References

1. Articolo L, Kusy RP. Influence of angulation on the resistance to sliding in fixed appliances. Am J Orthod Dentofacial Orthop 1999;115:39-51.

2. Kusy RP. Influence of force systems on archwire-bracket combinations. Am J Orthod Dentofacial Orthop 2005;127:333-42.

3. Kusy RP, Whitley JQ. Friction between different wire-bracket configurations and materials. Semin Orthod 1997;3:166-77.

4. Khambay B, Millett D, McHugh S. Evaluation of methods of archwire ligation on frictional resistance. Eur J Orthod 2004;26:327-332.

5. Nanda R. Biomechanical considerations in sliding mechanics, In: Nanda R. Biomechanics in clinical orthodontics. 1st ed. Philadelphia: WB Saunders; 1997. p. 190-1.

6. Chimenti C, Franchi L, Di Giuseppe MG, Lucci M. Friction of orthodontic elastomeric ligatures with different dimensions. Angle Orthod 2005;75:421-5.

7. Tselepis M, Brockhurst P, West VC. The dynamic frictional resistance between orthodontic brackets and arch wires. Am J Orthod Dentofacial Orthop 1994;106:131-8.

8. Kusy RP, Whitley JQ. Influence of archwire and bracket dimensions on sliding mechanics: derivations and determinations of the critical contact angles for binding. Eur J Orthod 1999;21:199-208.

9. Kusy RP. Ongoing innovations in biomechanics and materials for the new millennium. Angle Orthod 2000;70:366-76.

10. Pizzoni L, Ravnholt G, Melsen B. Frictional forces related to self-ligating brackets. Eur J Orthod 1998;20:283-291.

11. Marques ISV, Araújo AM, Gurgel JA, Normando D. Debris, roughness and friction of stainless steel archwires following clinical use. Angle Orthod 2010;80:521-7.

12. Arun AV, Vaz AC. Frictional characteristics of the newer orthodontic elastomeric ligatures. Indian J Dent Res 2011;22:95-9.

13. Cunha AC, Marquezan M, Freitas AOA, Nojima LI. Frictional resistance of orthodontic wires tied with 3 types of elastomeric ligatures. Braz Oral Res 2011;25:526:30.

14. Fleming PS, DiBiase AT, Lee RT. Self-ligating appliances: evolution or revolution? Aust Orthod J 2008;24:41-9.

15. Ehsani S, Mandich M, El-Bialy TH, Flores-Mir C. Frictional resistance in self-ligating orthodontic brackets and conventionally ligated brackets. Angle Orthod 2009;79:592-601.

16. Frank CA, Nikolai RJ. A comparative study of frictional resistances between orthodontic bracket and arch wire. Am J Orthod 1980;78:593-609.

17. Bednar JR, Gruendeman GW, Sandrik JL. A comparative study of frictional forces between orthodontic brackets and arch wires. Am J Orthod Dentofacial Orthop 1991;100:513-22.

18. Moore MM, Harrington E, Rock WP. Factors affecting friction in the pre-adjusted appliance. Eur J Orthod 2004;26:579-583.

19. Hamdan A, Rock P. The effect of different combinations of tip and torque on archwire/bracket friction. Eur J Orthod 2008;30:508-14.

20. Cordasco G, Farronato G, Festa F, Nucera R, Parazzoli E, Grossi GB. *In vitro* evaluation of the frictional forces between brackets and archwire with three passive self-ligating brackets. Eur J Orthod 2009;31:643-6.

21. Griffiths HS, Sherriff M, Ireland AJ. Resistance to sliding with 3 types of elastomeric modules. Am J Orthod Dentofacial Orthop 2005;127:670-5.

22. GIMP. Available from: URL: www.gimp.org

23. Whitley JQ, Kusy RP. Resistance to sliding of titanium brackets tested against stainless steel and beta-titanium archwires with second-order angulation in the dry and wet states. Am J Orthod Dentofacial Orthop 2007;131:400-11.

24. Thorstenson GA, Kusy RP. Effect of archwire size and material on the resistance to sliding of self-ligating brackets with second-order angulation in the dry state. Am J Orthod Dentofacial Orthop 2002;122:295-305.

25. Thorstenson GA, Kusy RP. Comparison of resistance to sliding between different self-ligating brackets with second-order angulation in the dry and saliva states. Am J Orthod Dentofacial Orthop 2002;121:472-82.

26. Thorstenson GA, Kusy RP. Resistance to sliding of self-ligating brackets versus conventional stainless steel twin brackets with second-order angulation in the dry and wet (saliva) states. Am J Orthod Dentofacial Orthop 2001;120:361-70.

27. Downing A, Mccabe JF, Gordon PH. The effect of artificial saliva on the frictional forces between orthodontic brackets and archwires. Br J Orthod 1995;22:41-6.

28. Toogood R. Personal communication August 22, 2012.

29. Thorstenson GA, Kusy RP. Effects of ligation type and method on the resistance to sliding of novel orthodontic brackets with second-order angulation in the dry and wet states. Angle Orthod 2003;73:418-30.

30. Leander D, Kumar J. Comparative evaluation of frictional characteristics of coated low friction ligatures – super slick ties with conventional uncoated ligatures. Indian J Dent Res 2011;22:90-4.

31. Swartz ML. Fact or friction: the clinical relevance of in vitro steady-state friction studies. J Clin Orthod 2007;41:427-32.

32. Sirisaowaluk N, Kravchuk O, Ho CTC. The influence of ligation on frictional resistance to sliding during repeated displacement. Aust Orthod J 2006;22:141-6.

33. Krishnan M, Kalathil S, Abraham KM. Comparative evaluation of frictional forces in active and passive self-ligating brackets with various archwire alloys. Am J Orthod Dentofacial Orthop 2009;136:675-82.

34. Henao SP, Kusy RP. Evaluation of the frictional resistance of conventional and self-ligating bracket designs using standardized archwires and dental typodonts. Angle Orthod 2004;74:202-11.

35. O'Reilly D, Dowling PA, Lagerstom L, Swartz ML. An ex vivo investigation into the effect of bracket displacement on the resistance to sliding. Br J Orthod 1999;26:219-27.

36. Hain M, Dhopatkar A, Rock P. The effect of ligation method on friction in sliding mechanics. Am J Orthod Dentofacial Orthop 2003;123:416-22.

37. Braun S, Bluestein M, Moore K, Benson G. Friction in perspective. Am J Orthod Dentofacial Orthop 1999;115:619-27.

Chapter 4. General Discussion, Recommendations, and Conclusion

4.1 General Discussion

4.1.1 Strengths

Traditionally, experiments measured frictional force (Fx) at the wire level. With technology advances, this three-dimensional (3D) friction device measured forces (F) and moments (M) at the bracket level in three directions, specifically Fx, Fy, Fz, Mx, My, and Mz. In fact, this study was the first to introduce moment effects experienced by a bracket. Understanding the friction phenomenon from a 3D perspective provided valuable novel information. Furthermore, the marginal errors of this device were acceptable, as was the high intra-rater reliability. In comparison to other studies, the strengths of this study included a large and justified sample size, testing a range of second-order angulations in dry and wet states, reporting the critical contact angle for binding, utilizing standard techniques for elastomer placement and saliva application, and an absence of confounding variables from elastomers, brackets, wires, or investigators.

4.1.2 Limitations

The vast methodological differences between studies make comparisons of the literature complicated and could account for inconsistent results.[1] Furthermore, with no standards for orthodontic materials, manufacturers tolerances in bracket and wire geometry could also contribute to variations in study results. Additionally, in-vitro studies do not imitate complex in-vivo situations,[2] as oral conditions, including muscular and occlusal forces and tooth movement through bone, are challenging to replicate.[3] Therefore, developing clinically relevant methodologies are limitations of laboratory experiments.[4] On the other hand, these laboratory experiments provide the luxury of investigating specific mechanical interactions without the myriad of complicated in-vivo factors, such as ethics approval, patient health, age, gender, and tooth geometry.

A limitation of this study was the requirement to use small wire translation increments in order to stay in the middle of the wire to minimize the change in effective stiffness of the wire. Due to the design of the test apparatus, inter-bracket distance was not a constant, although distance variation during the test was decreased to diminish the effect on resistance to sliding from a change in wire stiffness. The time consuming nature of both the imaging software and application of surface epoxy on the dowel were disadvantages. The wire clamp design may have contributed to moment effects. Although wet states were tested over five days, storing the human saliva in a household freezer could have introduced protein denaturation, thereby changing the original integrity of saliva.

4.2 Recommendations

As the cause of frictional resistance between a bracket and wire is multifactorial, future research should investigate different bracket manufacturers and materials, various wire sizes and materials, assorted tooth numbers, and alternate ligation methods. For instance, studying the effect of pre-loaded normal forces on a bracket and effect of wire curvature would be innovative. Moreover, evaluating both static and kinetic friction on a segment of brackets experiencing oral functions would be valuable. These functional activities may involve simulating vibrations, perturbations, or vertical displacements from occlusal contacts.

In today's era, 3D technology will surpass traditional friction testing methods, with its escalating list of advantages. Modifications of the next generation 3D friction device should include a constant, but experimentally variable, inter-bracket distance. Investigating all the force and especially moment effects at numerous second-order angulations, not only 0° and 5° as in this study, would be insightful. Continued testing in both dry and wet states would be recommended with the utilization of -80°C freezer to store human saliva. Other recommendations to save investigator time should include utilization of a translucent dowel to promote composite resin curing and more efficient imaging software. A more secure wire clamp design would ensure no rotational or lateral wire movements contributing to moment effects.

Importantly, frictional studies need standardized testing methods in order to compare results and make more sound conclusions. Collaboration between research groups to use the same device and/or protocol is feasible and advocated. High quality research studies will continue to unravel the friction phenomenon and optimistically, its clinical application.

4.3 Conclusion

The novelty of this 3D friction device includes measuring forces and moments in the x, y, and z directions at the bracket, not archwire, level. There was strong evidence for Fx, Fy, Fz, Mx, My, and Mz on the Damon Q self-ligating bracket to be significantly influenced by the effects of second-order angulation, elastomer, state, and all interactions. In fact, second-order angulation, elastomer, and the interaction of angulation and elastomer were the primary influencers. Overall, the ligation method was the dominant factor, with the mean difference more pronounced at higher angulations. Specifically, self-ligating bracket had less Fx and My compared to conventional bracket. Saliva had little effect or lubricious behavior on frictional force. Indeed, 3D technology should be the standard protocol for understanding the friction phenomenon, as current one-dimensional methods are limited in scope of information.

4.4 References

1. Downing A, Mccabe JF, Gordon PH. The effect of artificial saliva on the frictional forces between orthodontic brackets and archwires. Br J Orthod 1995;22:41-6.

2. Stefanos S, Secchi AG, Coby G, Tanna N, Mante FK. Friction between various self-ligating brackets and archwire couples during sliding mechanics. Am J Orthod Dentofacial Orthop 2010;138:463-7.

3. Tselepis M, Brockhurst P, West VC. The dynamic frictional resistance between orthodontic brackets and arch wires. Am J Orthod Dentofacial Orthop 1994;106:131-8.

4. Eliades T, Bourauel C. Intraoral aging of orthodontic materials: the picture we miss and its clinical relevance. Am J Orthod Dentofacial Orthop 2005;127:403-12.

Appendix. Chapter 3 Supplemental Tables, Figures, and Equations

Appendix A. Sample Size Calculation

To justify sample size:

$$n = \left(\sigma_{NE}^2 + \sigma_E^2\right)\left[\frac{\left(z_\beta + z_{\frac{\alpha}{2}}\right)^2}{\delta^2}\right]$$

n = sample size per group
σ_{NE} = standard deviation for no elastomeric ligation in Newton's
σ_E = standard deviation for elastomeric ligation in Newton's
z_β = z statistic beta, for beta of 0.1 = 1.28
$z_{\frac{\alpha}{2}}$ = z statistic alpha, for alpha of 0.05 = 1.96
δ = clinical difference = 0.5 Newton's

From Cordasco et al (2009), **n = 25** from **σ_{NE} = 0.379** and $\boldsymbol{\sigma_E = 0.665}$.

From Griffiths et al (2005), dry state, **n = 12** from **σ_{NE} = 0.27** and $\boldsymbol{\sigma_E = 0.46}$.

From Griffiths et al (2005), wet state, **n = 54** from **σ_{NE} = 0.52** and $\boldsymbol{\sigma_E = 1.01}$.

As illustrated, sample size per group ranged from 12 to 54.

To ensure adequate sample size, the largest sample size of 54 was selected. With 20% failure rate added as a margin of safety, the sample size per ligation group was calculated to be 65.

Equation was referenced from:
Rosner B. Fundamentals of Biostatistics. 7th ed. Boston: Brooks/Cole; 2010.

Appendix B. Intra-class Correlation Coefficient

A different investigator (RT) completed the imaging procedure for the same 10 pairs as the primary investigator (MF) and repeated the imaging, thereby measuring intra-rater reliability and comparing the two investigators to assess inter-rater reliability.

Table A. The intra-class correlation coefficient (ICC) of each investigator to assess intra-rater reliability (n=10). The ICC of two investigators to assess inter-rater reliability.

Investigator	ICC Displacement			ICC Angle		
	x	y	z	θ	γ	β
MF	0.99	0.98	0.98	0.98	0.72*	0.93
	(0.97. 1.0)	(0.94, 1.0)	(0.91, 0.99)	(0.86, 1.0)	(0.31, 0.92)	(0.82, 0.98)
RT	0.98	0.96	0.98	0.97	0.26*	0.61*
	(0.94, 1.0)	(0.85, 0.99)	(0.89, 0.99)	(0.88, 0.99)	(-0.46, 0.75)	(-0.03, 0.89)
MF/RT	0.99	0.97	0.95	0.98	0.21*	0.63*
	(0.95, 1.0)	(0.90, 0.99)	(0.76, 0.99)	(0.92, 1.0)	(-0.16, 0.66)	(-0.03, 0.90)

The upper and lower bound of 95% confidence interval (CI) are noted within the parenthesis.
*Correspond to ICC values below 0.8.

The second investigator's ICC ranged from 0.96 to 0.98 for most variables, but 0.26 for γ and 0.61 for β (Table A). Comparing both investigator's, ICC ranged from 0.95 to 0.99 for most variables, although 0.21 for γ and 0.63 for β (Table A). The primary investigator's intra-rater reliability was higher than the second investigator, especially for γ and β, likely from enhanced practice and meticulous utilization of GIMP.

The intra-rater reliability for MF shown in Figure A illustrates a trend towards overestimation of γ and β on repeated measurements. Noteworthy, the correlation of MF β was near 1.0, whereas other β and γ correlations were much lower. The intra-rater reliability for RT shown in Figure B illustrates a trend towards overestimation of γ on initial measurements and an overestimation of β on repeated measurements. The inter-rater reliability between MF and RT shown in Figure C illustrates either an overestimation for MF or underestimation for RT of γ and either an underestimation for MF or overestimation for RT of β.

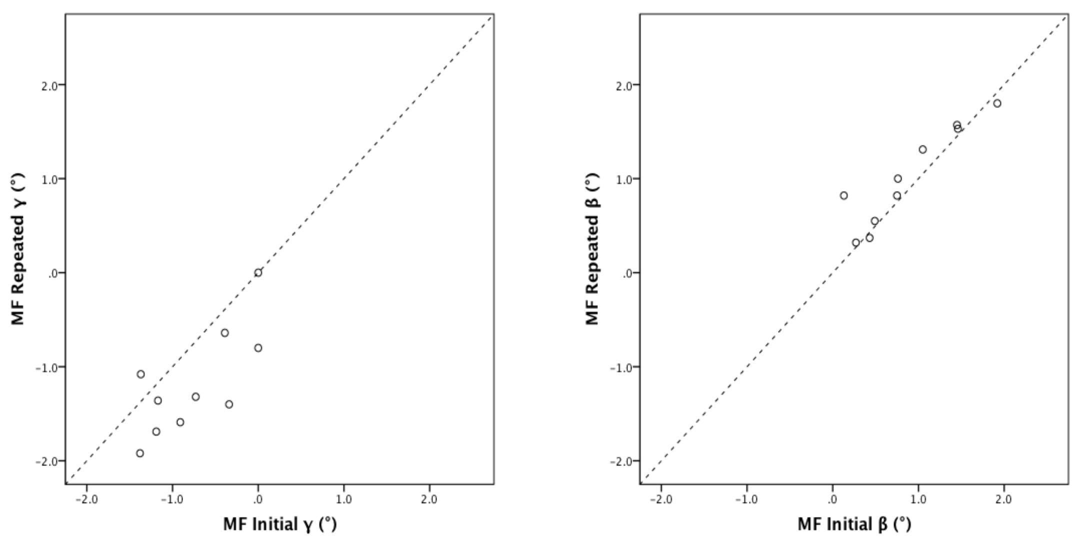

Figure A. Illustration of primary investigator's initial and repeated measurements for γ and β, where line represents y=x and denotes a perfect agreement.

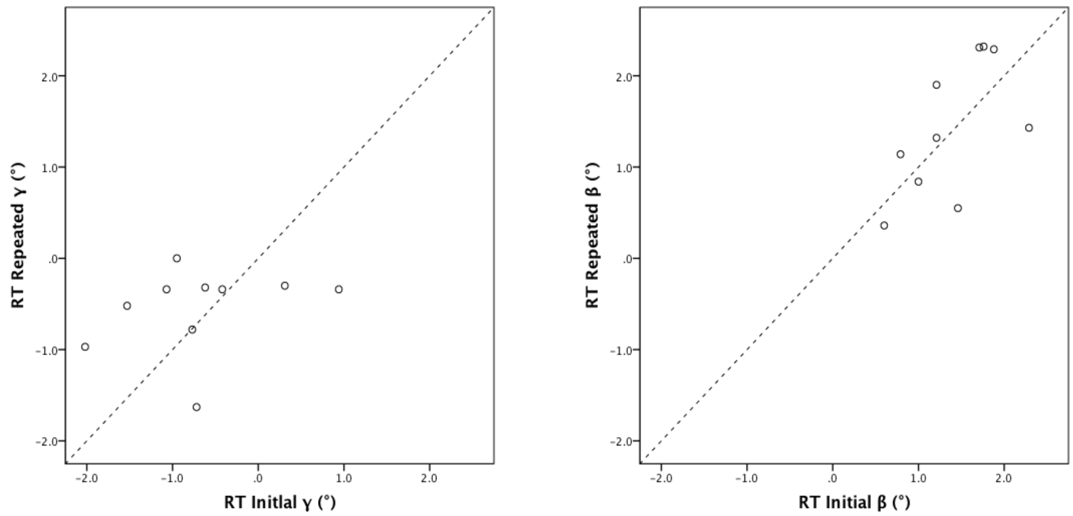

Figure B. Illustration of second investigator's initial and repeated measurements for γ and β, where line represents y=x and denotes a perfect agreement.

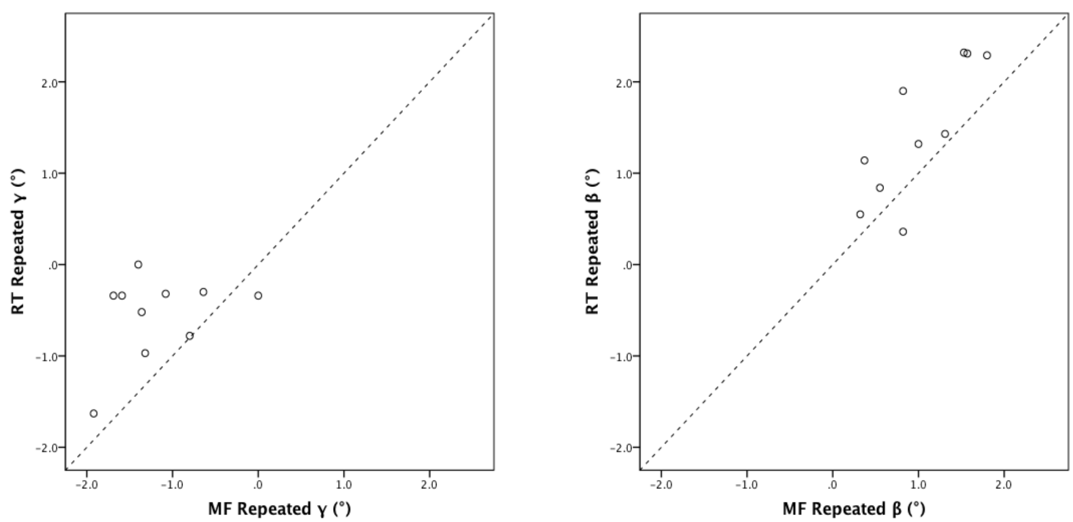

Figure C. Illustration of both investigator's repeated measurements for γ and β, where line represents y=x and denotes a perfect agreement.

Appendix C. Critical Angle Calculation

With quantities of archwire width (size), slot width (slot), and bracket width (width), the theoretical equation for θ_c (°) is approximately:

$$\theta_c = \frac{57.32[1 - \left(\frac{size}{slot}\right)]}{(\frac{width}{slot})}.$$

For the Damon Q self-ligating bracket and 0.018 x 0.025" archwire used in this study, the approximate theoretical θ_c is 2.08°, with size of 0.018", slot of 0.022", and width of 0.110". Therefore, sliding mechanics should be initiated when $\theta \approx \theta_c$ or 2.08° in this experiment.

Equation was referenced from:
Kusy RP, Whitley JQ. Influence of archwire and bracket dimensions on sliding mechanics: derivations and determinations of the critical contact angles for binding. Eur J Orthod 1999;21:199-208.

Appendix D. Boxplots of Fy, Fz, Mx, Mz

A **B**

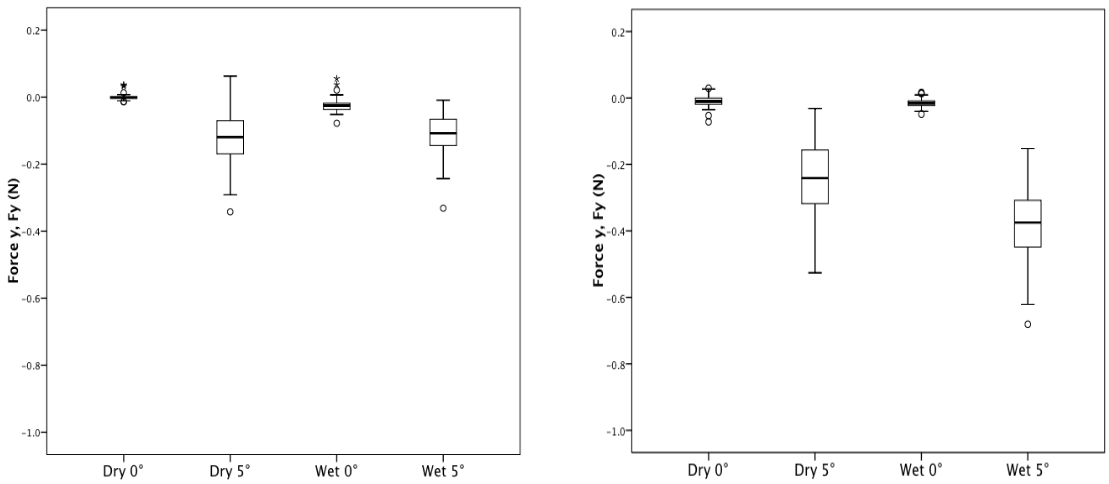

Figure D. **A,** Boxplot of Fy, with no elastomeric ligation (self-ligating bracket), for dry and wet states at 0° and 5°. **B,** Boxplot of Fy, with elastomeric ligation (conventional bracket), for dry and wet states at 0° and 5°.

A **B**

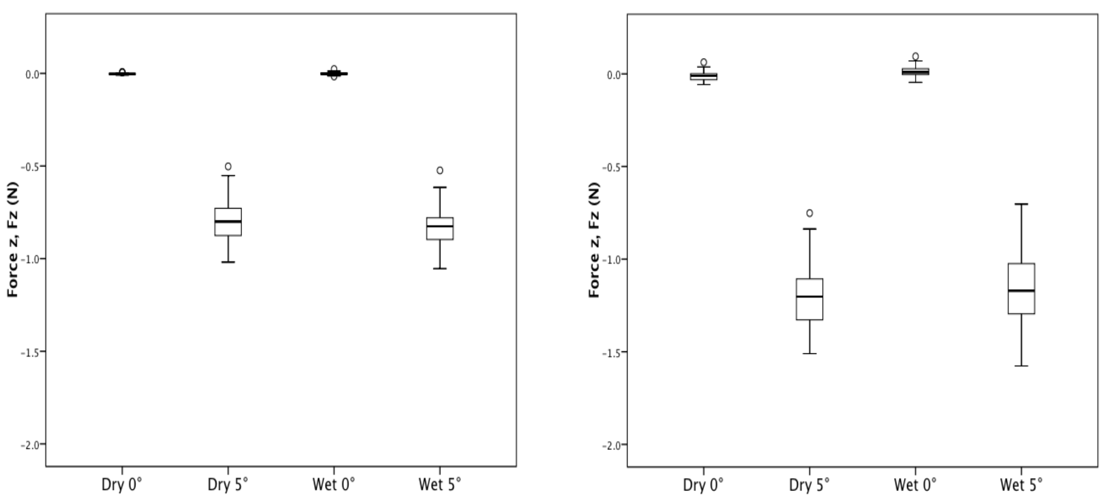

Figure E. **A,** Boxplot of Fz, with no elastomeric ligation (self-ligating bracket), for dry and wet states at 0° and 5°. **B,** Boxplot of Fz, with elastomeric ligation (conventional bracket), for dry and wet states at 0° and 5°.

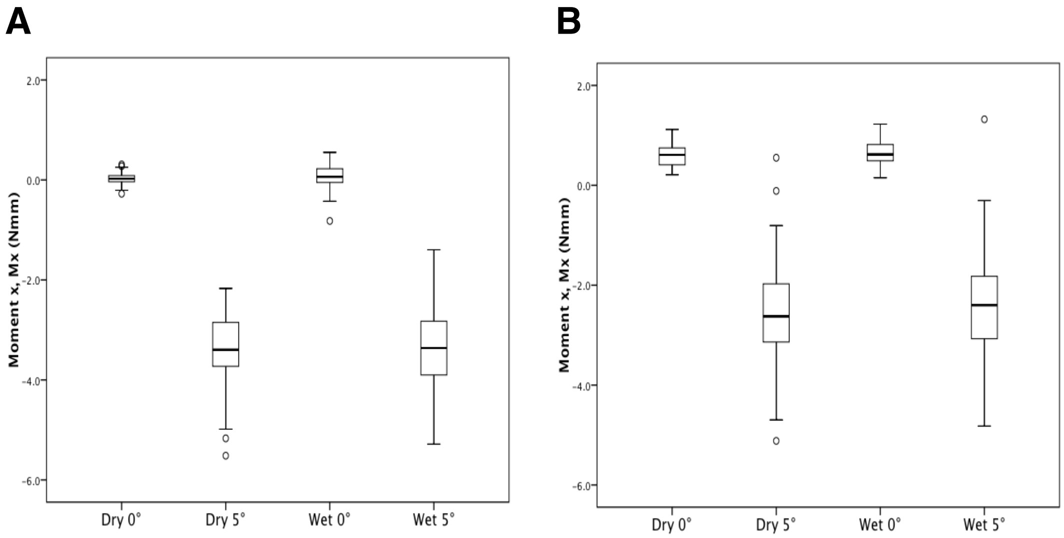

Figure F. **A,** Boxplot of Mx, with no elastomeric ligation (self-ligating bracket), for dry and wet states at 0° and 5°. **B,** Boxplot of Mx, with elastomeric ligation (conventional bracket), for dry and wet states at 0° and 5°.

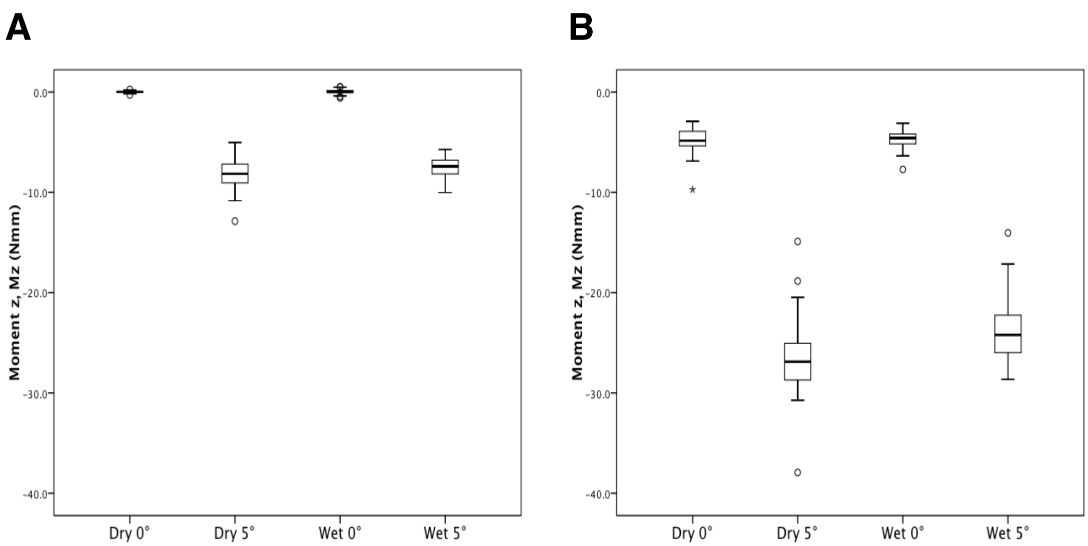

Figure G. **A,** Boxplot of Mz, with no elastomeric ligation (self-ligating bracket), for dry and wet states at 0° and 5°. **B,** Boxplot of Mz, with elastomeric ligation (conventional bracket), for dry and wet states at 0° and 5°.

Appendix E. Univariate Analysis for Fy, Fz, Mx, and Mz

Table B. Univariate analysis for Fy, Fz, Mx, and Mz (n=123).

Effects	Outcome	F	*P*	η_p^2
Elastomer	Fy	204.1	<0.001*	0.63
	Fz	252.5	<0.001*	0.68
	Mx	79.8	<0.001*	0.40
	Mz	4475.8	<0.001*	0.97
State	Fy	38.3	<0.001*	0.24
	Fz	0.8	0.382	0.01
	Mx	1.8	0.182	0.02
	Mz	21.8	<0.001*	0.15
State + Elastomer	Fy	24.2	<0.001*	0.17
	Fz	10.4	0.002*	0.08
	Mx	0.1	0.715	0.001
	Mz	9.8	0.002*	0.08
Angulation	Fy	1181.3	<0.001*	0.91
	Fz	9764.8	<0.001*	0.99
	Mx	2365.8	<0.001*	0.95
	Mz	9491.0	<0.001*	0.99
Angulation + Elastomer	Fy	266.6	<0.001*	0.69
	Fz	327.0	<0.001*	0.73
	Mx	3.4	0.068	0.03
	Mz	1883.5	<0.001*	0.94
State + Angulation	Fy	15.1	<0.001*	0.11
	Fz	0.3	0.577	0.003
	Mx	0.4	0.534	0.003
	Mz	30.0	<0.001*	0.20
State + Angulation + Elastomer	Fy	48.4	<0.001*	0.29
	Fz	4.3	0.040*	0.03
	Mx	0.011	0.915	9.4×10^{-5}
	Mz	13.3	<0.001*	0.10

F=F statistic, $P \leq 0.05$ was significant (denoted *), η_p^2 = Partial Eta Squared.
Degrees of freedom (1, 121) for each effect.

Appendix F. Mean and Standard Deviation

Table C. Mean and standard deviations for Fx, Fy, Fz, Mx, My, and Mz (n=123).

Outcome		Dry State				Wet State			
		No Elastomer		**Elastomer**		**No Elastomer**		**Elastomer**	
		Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Fx	**0°**	-0.0004	0.0030	0.7396	0.1606	0.0015	0.0074	0.7372	0.1248
	5°	1.1115	0.1801	4.0015	0.4360	1.0471	0.1409	3.6460	0.4608
Fy	**0°**	0.0003	0.0090	-0.0108	0.0169	-0.0247	0.0202	-0.0158	0.0132
	5°	-0.1230	0.0752	-0.2467	0.1194	-0.1131	0.0607	-0.3749	0.1115
Fz	**0°**	-0.0023	0.0032	-0.0119	0.0253	-0.0017	0.0066	0.0110	0.0272
	5°	-0.7936	0.1096	-1.1992	0.1593	-0.8340	0.0972	-1.1527	0.2049
Mx	**0°**	0.0318	0.1097	0.5958	0.2118	0.0612	0.2369	0.6555	0.2384
	5°	-3.3774	0.7152	-2.5769	1.0949	-3.2987	0.8027	-2.4475	1.2046
My	**0°**	-0.0082	0.0302	-0.0556	0.2041	-0.0206	0.0303	-0.0771	0.2390
	5°	10.2631	1.6241	13.6975	1.2265	10.2550	1.1844	13.0543	1.4134
Mz	**0°**	0.0120	0.0909	-4.7865	1.2128	0.0281	0.2176	-4.6784	0.8063
	5°	-8.1279	1.4428	-26.6114	3.3084	-7.6013	1.0696	-23.9603	2.9224

SD=Standard Deviation.

Appendix G. Profile Plots for Fx and My

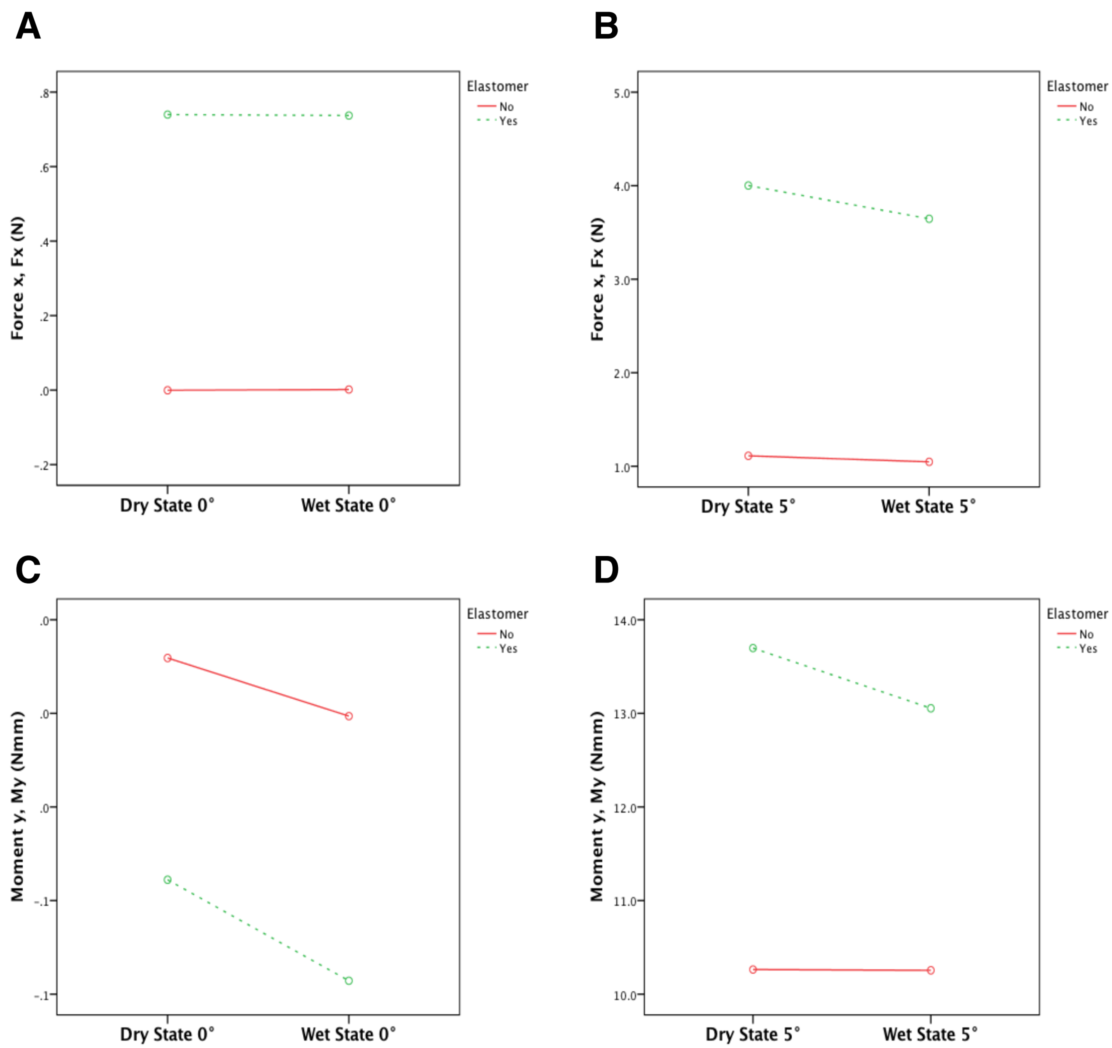

Figure H. **A,** Profile plots of Fx for dry and wet states at 0°. **B,** Profile plots of Fx for dry and wet states at 5°. **C,** Profile plots of My for dry and wet states at 0°. **D,** Profile plots of My for dry and wet states at 5°.