11-27-2019 5:00 PM

The Effect of Pigmentation on Thermoplastic and Thermoset Elastomeric Power Chain

William Taylor
The University of Western Ontario

Supervisor
Tassi, Ali
The University of Western Ontario

Graduate Program in Orthodontics
A thesis submitted in partial fulfillment of the requirements for the degree in Master of Clinical Dentistry

1 Abstract

Background: Elastomeric chains have been used in orthodontics for nearly 60 years. With the advent of new materials and the popularity of colored chains the level of force delivery has been proven to vary from company to company.

Aim: The purpose of the study was to determine the effect of pigmentation on force levels and their degradation over time in orthodontic power chain of different chain types and manufactures.

Materials & Methods: Groups consisted of closed power chain from American Orthodontic (AO) thermoplastic (TP) in 5 colors, AO thermoset (TS) in 2 colors, Ormco TP in 4 colors, Ormco TS in 2 colors, and Rocky Mountain Orthodontics (RMO) TS in 5 colors (18 groups total, 10 chain samples in each group). Testing was performed over a period of 6 weeks at intervals of initial (T0), 1 hour (T1), 1 day (T2), 1 week (T3), 2 weeks (T4), 4 weeks (T5), and 6 weeks (T6). At each timepoint, an Instron Universal Testing Machine was utilized to stretch a sample to 25mm and record the force level. After each test, the chain samples were placed on the 3D printed arch model, stretched 25mm from tooth #23 to #26 and stored in distilled water at 37^0C between time points to simulate canine retraction in the oral environment.

Results: In general, force levels of all chains significantly decreased at each time point, but the decrease was larger for the TP groups early on and leveled off at the later time points. The TS groups exhibited a more gradual and continuous decrease in force values while maintaining overall higher force values. Chain pigmentation had a significant effect on force levels at all time points within each manufacturer and chain material. Chains containing blue pigment, in both TP and TS chain types, degraded faster and delivered significantly lower force values in all colored groups at most time points. In addition, at weeks 4 and 6, AO TS grey had a significantly lower mean force than the corresponding AO TS clear.

Conclusions: Pigmentation played a significant role in force levels and their degradation over time, but the specific pattern is not consistent between manufacturer or chain material.

Keywords

Power chain, Force degradation, Elastomeric, Pigmentation, Orthodontics, Thermoset, Thermoplastic

Lay Person Summary

When people seek orthodontic care, a common concern is spacing between their teeth. Orthodontic power chain is an elastic that gets tied from tooth to tooth to create tooth movement to close these spaces. This chain can be made from different materials (thermoplastic and thermoset) and for esthetic purposes it is supplied in different colors. This chain is also supplied by different manufactures which differ based on manufacturing techniques.

Aim of this research was to determine the effect of color on force levels and its degradation over time in orthodontic power chain of different chain types and manufactures.

Materials & Methods: Groups consisted of 7 different colors and 2 different chain types from 3 different companies. Groups were tested over a period of 6 weeks at intervals of initial, 1 hour, 1 day, 1 week, 2 weeks, 4 weeks, and 6 weeks. At each timepoint, an Instron Universal Testing machine was used to stretch the chain and record the force level. After testing, the samples were placed on a replica of a common orthodontic situation in a simulated oral environment.

Results: In general, the forces delivered by all chains decreased at each time point, but the decrease was larger in one of the chain types (thermoplastic) early on and leveled off at later time points. The other group (thermoset) exhibited a more gradual and continuous decrease while maintaining overall higher force values. Chains containing blue pigment in both types degraded faster and delivered significantly lower force values.

Conclusions: Color played a significant role in force delivery and their decrease over time, but it wasn't consistent between manufacturer or material.

Acknowledgments

I would like to extend a sincere thank you to all those who have supported me over the past three years. Without your guidance, patience and assistance completion of my project would not have been possible.

Dr. Ali Tassi, Western University, Department of Graduate Orthodontics, for graciously offering to supervise another student's thesis under your already packed schedule. Your guidance, thoughts and additions are very much appreciated.

Dr. Antonios Mamandras, Western University, Department of Graduate Orthodontics, for being a wonderful Department Head and developing an Orthodontic program that provides the best student experience. Your smile and calm reassurance will be missed in our program, but your legacy will live on.

Dr. Amin Rizkalla, Western University, Division Medical Biophysics Schulich School of Medicine and Dentistry, for your expertise, encouragement and for the use of your Lab.

Drs Mark Pus and Bruce Hill for being members of my examination committee and clinical instructors. It has been an honour and pleasure to learn from two of the best.

My co-resident's past and present. It has been an amazing ride!

My mother, Alma, and my late father, William, for your love, support and understanding.

My Wife, Janet and children, Brett and Alex, for going on this life changing journey and believing in me with unconditional love and understanding.

Table of Contents

1 Abstract i
Acknowledgments iii
Table of Contents iv
List of Tables vii
List of Figures viii
List of Appendices ix
List of Abbreviations x
Chapter 1 1
1 Introduction 1
1.1 Orthodontic Force systems and Durations 2
1.2 Elastomeric Chain Composition 4
1.3 Physical Properties 4
1.3.1 Force Decay in Elastomers 4
1.3.2 Thermoset vs Thermoplastic Elastomers 6
1.3.3 The Effect of Manufacturing 7
1.3.4 The Effect of the Environment on Force Decay 8
1.3.5 The effect of Sterilization on Force Decay 9
1.3.6 The Effect of Storage Media on Force Decay 9
1.3.7 The Effect of Pre-Stretching on Force Decay 10
1.3.8 The Effect of Different Ligation Designs on Force Decay 10
1.4 The Effect of Pigmentation 11
1.5 Problem Statement 13
1.6 Purpose 14
1.7 Hypothesis 14

Chapter 2 15

2 Materials and Methods 15

2.1 Elastomeric Chains 15

2.2 Model Fabrication 18

2.3 Testing Conditions and Data Recording 19

2.4 Pilot Study 21

2.5 Data Analysis 22

Chapter 3 23

3 Results 23

3.1 Comparison of Thermoplastic Force Levels 23

3.1.1 American Orthodontics TP 23

3.1.2 Ormco TP 24

3.2 Comparison Thermoset Force Levels 25

3.2.1 American Orthodontics TS 25

3.2.2 Ormco TS 26

3.2.3 Rocky Mountain Orthodontics TS 27

Chapter 4 31

4 Discussion 31

4.1 Methodology 31

4.2 Force Levels 33

4.3 Effect of Color 34

4.4 Effect of Manufacturer 35

4.5 Clinical Applications 35

4.6 Clinical Significance 36

4.7 Limitations of this Study 36

4.8 Strengths of this Study 37

4.9 Suggestions for Future Research 37

Chapter 5 38

5 Conclusions 38

References 39

Appendices 42

Curriculum Vitae 64

List of Tables

Table 1: Investigated Power Chains 18

Table 2: Average Force levels at all time points (with Standard Deviation in Parentheses) separated by TS and TP. 28

Table 3. Percentage of Initial Force Remaining for AO Elastomeric Chains at Different Time Intervals.. 29

Table 4. Percentages of Initial Force Remaining for Ormco Elastomeric Chains at Different Time Intervals 29

Table 5. Percentages of Initial Force Remaining for RMO Elastomeric Chains at Different Time Intervals 30

List of Figures

Figure 1: Total Sample comprised of 18 groups 17

Figure 2: 3D printed model with power chain stretched from canine to first molar 19

Figure 3: Instron testing machine, A. Frontal view of power chain mounting hooks, B. 10 N Instron load cell, C. Great Lakes model dryer, D. 21

Figure 4. Thermoplastic Chain Decay Over Time 24

Figure 5. Thermoset Chain Decay Over Time 26

List of Appendices

Appendix A: Raw Force (N) Data for RMO 42

Appendix B: Raw Force (N) Data for AO 43

Appendix C: Raw Force (N) Data for Ormco.. 45

Appendix D: Force Displacement Behavior AO 46

Appendix E: Force Displacement Behavior Ormco 50

Appendix F: Force Displacement Behavior RMO.. 53

Appendix G. Mean Force Plots at Each Time Point for TP Chains 56

Appendix H: Mean Force Plots at Each Time Point for TS Chains 60

List of Abbreviations

AO = American Orthodontics

ATP = American Orthodontics Thermoplastic Power Chains

ATPB = American Orthodontics Thermoplastic Blue Power Chain

ATPC = American Orthodontics Thermoplastic Clear Power Chain

ATPG = American Orthodontics Thermoplastic Grey Power Chain

ATPR = American Orthodontics Thermoplastic Red Power Chain

ATPY = American Orthodontics Thermoplastic Yellow Power Chain

ATS = American Orthodontics Thermoset Power Chain

ATSC = American Orthodontics Thermoset Clear Power Chain

ATSG = American Orthodontics Thermoset Grey Power Chain

OTP = Ormco Thermoplastic Power Chain

OTPB = Ormco Thermoplastic Blue Power Chain

OTPG = Ormco Thermoplastic Silver Power Chain

OTPR = Ormco Thermoplastic Red Power Chain

OTPY = Ormco Thermoplastic Yellow Power Chain

OTS = Ormco Thermoset Power Chain

OTSC = Ormco Thermoset Clear Power Chain

OTSG = Ormco Thermoset Grey Power Chain

RMO = Rocky Mountain Orthodontics

RTS = Rocky Mountain Orthodontics Thermoset Power Chain

RTSB = Rocky Mountain Orthodontics Thermoset Blue Power Chain

RTSC = Rocky Mountain Orthodontics Thermoset Clear Power Chain

RTSG = Rocky Mountain Orthodontics Thermoset Grey Power Chain

RTSR = Rocky Mountain Orthodontics Thermoset Red Power Chain

RTSY = Rocky Mountain Orthodontics Thermoset Yellow Power Chain

Thermoplastic = TP

Thermoset = TS

Chapter 1

Review of the Literature

1 Introduction

Orthodontic tooth movement is utilized to establish a well indigitated occlusion that is both functional and esthetic. A light continuous force is generally accepted as being ideal to ensure minimal patient discomfort while preventing physiologic resorption and also allowing for efficient and predictable tooth movement. There exist many techniques to deliver a physiologically friendly delivery of this force, but they vary in complexity and cost.

When discussing space closure, the most common methods used today are coil springs, multi-loop wires, elastic threads and elastomeric chains. Many of these methods are known to have a gradual loss of effectiveness over time due to stress relaxation. Coil springs are generally fabricated from nickel titanium and are much more costly than some of the other methods. They also tend to be less hygienic and have a tendency to irritate the gingiva. [(1, 2)]According to a systematic review held by Barlow et al., the rate of retraction by elastomeric chain is similar to 150 and 200 g NiTi coil springs, besides the latter is more expensive. [(3)]

Multi-loop wires tend to be time consuming and difficult to bend while also requiring patients to return for reactivation.

Synthetic elastomeric chains have been around since the 1960's and have many clinical advantages: they are inexpensive; compatible with soft tissues; their insertion and removal require minimal chair time; not dependent on patient compliance; and can provide light or heavy forces to deliver appropriate tooth movement. They are however not without limitations. When exposed to the oral environment they absorb moisture, permanently stain, and suffer permanent deformation.

Ultimately this results in a gradual loss of effectiveness which begins with a rapid loss of force in the first 24 hours due to stress relaxation. [4]

1.1 Orthodontic Force systems and Durations

At the heart of orthodontics is the process by which a pressure is applied to a tooth and this pressure then elicits a physiologic reaction that results in bone resorption and deposition. The goal for efficient tooth movement is to avoid excessive forces that result in undermining resorption. With excessive forces blood vessels are occluded which prevents the necessary cellular events from happening and sterile necrosis occurs. This leaves us theoretically trying to apply a light continuous force that is sufficiently strong enough to achieve the desired tooth movement. [5]

Some controversy exists as to what constitutes an ideal force level for any given tooth movement. A.M Schwarz generated data that suggested that the applied force should not exceed the capillary blood pressure of 20 to 26 gm/sqcm of root surface. He believed that this would produce what is now termed frontal resorption. [6] Storey and Smith developed the designation of subthreshold force, threshold force, optimum force and maximum force. They determined that absolute force values were not attainable and that instead only a range of force values could be used as a general guideline for clinical use. [7] This level will depend on multiple factors such as type and direction of tooth movement, the root surface area, the amount and density of surrounding alveolar bone, and general individual variation. [1] [8] Ren et al. conducted a systematic literature review and concluded that no evidence could be extracted about optimal force levels and that more studies are required. [9] Most elastomeric chain studies focus on the force needed for optimal canine retraction. R.J. Nikolai presented that for a maxillary canine

210gm (2.1 N) and 365gm (3.6 N) should be sufficient for proper bodily movement and crown movement, respectively. [10] Boester et al. looked at force levels of 2, 5, 8, and 11 ounces. They concluded that the 2-ounce group produced significantly less tooth movement than the others and that there were no significant differences among the 5,8, and 11ounce groups (1.4 N, 2.3 N, 3.1 N). [11]

When considering the duration of the applied force, orthodontic forces can be described as being interrupted, intermittent and continuous. To differentiate between the three, one needs to consider the rate of decay of the applied force apparatus.

Interrupted orthodontic force levels decline to zero between appointments and need to be reactivated to continue with desired tooth movement. If this force level is light, then the tooth will only move a small distance by frontal resorption and will then need to be reactivated to get further movement. If the initial force is excessive and the tooth moves by undermining resorption then the tooth will move rapidly once this occurs. The important concept here is that the system needs time to regenerate and repair before the force is applied again to prevent damage to both the dental and osseous structures.

Intermittent forces can be described has having cyclic pattern of activation and reduction to zero multiple times between scheduled appointments. This type of activation is generally achieved by patient activated appliances such as headgear wear and interarch elastics.

Continuous forces never reduce to zero and ideally are maintained at some appreciable fraction between appointments. If the ideal amount of force is maintained, then a smooth progression of movement should be expected. If that force level is excessive and continuous then movement will be limited until the undermining resorption can occur and then a rapid movement will happen until compression of the tissue occurs again and then the system will undergo another round of undermining resorption. [5]

1.2 Elastomeric Chain Composition

The actual applied strength of the elastomeric chains is affected by both intrinsic and extrinsic factors. Extrinsic factors are generally impossible to control. These include fluctuating temperature, pH, salivary enzyme levels, mastication, and patients' level of oral hygiene. Intrinsic factors included such things as product shape and size, production methods, and material composition. The exact compositions are kept secret by the manufactures, but they are generally formed from clear resin or polyurethane based polymers. [12] These polymers have a weak molecular attraction consisting of primary and secondary bonds that initially display a spiral pattern. When the polymer is subjected to a force the resultant deformation causes the molecular chains to unfold into a linear pattern because of the weak secondary bonds. When the force is released recovery of the initial pattern is possible because of the cross linking. Permanent deformation occurs when the force applied is greater and causes rupture of both the primary and secondary bonds. [13, 14] Elastomeric chains are synthetic elastomers (usually referred to as "alastiks") that can be either thermoplastic or thermoset.

1.3 Physical Properties

1.3.1 Force Decay in Elastomers

There have been numerous studies describing the physical properties of elastomeric chains dating back to the 1970's. Comparisons have been difficult to make due to differences in study designs and changing materials.

Andreasen and Bishara compared synthetic (Alastiks) elastomeric chains to rubber (latex) elastics. They found that after 24 hours that elastic chains loose 74% of their force levels and for the remaining 3 weeks a total rate of decay of only another 8%. Therefore, they were considered to maintain a reasonably constant force level. This led them to suggest that since the initial force is much greater than the force applied to teeth one hour later that we should choose elastics with four times the wanted force levels. [4]

Hershey and Reynolds extended the time period to 6 weeks and accounted for simulated tooth movements at a rate of 0.25 and 0.5mm per week. Their results demonstrated that all modules lost approximately 50% within the first 24hours and were able to maintain an average of 40% of the initial force after 4 weeks and a very similar level after 6 weeks. Simulated tooth movement led to an increase in the rate of force loss. At a rate of 0.25mm one third of the initial force remained after one month, while one quarter remained for the same time period with a rate of 0.5mm. The observed substantial differences in the initial force levels between the different companies led them to conclude that a force gauge should be used to determine the initial loads of the chains to determine proper applied force. [15]

Similar to Andreasen and Bishara, Wong found that synthetic elastics had a 73% decay in force during the first day with a slower rate over the next 21 days. More specifically he found that the greatest rate of decay occurred during the first 3 hours. He also found considerable variation in initial force delivery ranging from 641g to 342 g with all reducing to an average of 171g after one day. [16]

More recently Evans et al. evaluated the ability of elastomeric chain (3M) to provide sufficient force to move teeth over a 16-week period both in-vivo and in-vitro. It was a split mouth design where the chain was replaced after 28 days on one side (altered) but not replaced and left in for the full 16 weeks on the other (unaltered). They found that the mean space closure at the altered sites was minimally greater than that observed at the paired unaltered sites. The unaltered (16 week) continued to move teeth from both a statistically and clinically significant standpoint. After 16 weeks the chain displayed less than 100 g of force but clinically continued to move teeth. [17]

1.3.2 Thermoset vs Thermoplastic Elastomers

In 1985 Killiany tested the new synthetic elastomeric chain, Energy Chain, from Rocky Mountain Orthodontics (RMO) and compared it to American Orthodontics (AO) short loop chain. At the time it was not known that RMO was in fact a thermoset chain. Force degradation tests were conducted, and it was found that initially the plastic chain from AO applied 375 g of force whereas the RMO chain delivered 330g. After 4 weeks the RMO chain still maintained 65.8% of its initial force vs only 33.4% for the AO chain. This demonstrated a significant improvement in the manufacturing process and further development of chain material. [18]

Mirhashemi et al set out to compare elastomeric chains that claim to offer memory (thermoset) vs traditional (thermoplastic) chains. They took three brands AO, GAC, and Ortho-Technology. Force decay measurements were obtained at various intervals over 4-weeks. Additionally, they measured the amount of extension needed to obtain 200g forces. They found that traditional chains were significantly different and retained ~30%-40% of force over the 4-week period. Memory chains demonstrated more constant force and retained 60% of the force. The memory chains required more elongation than traditional chains to deliver the same force. This led them to conclude that memory chains have superior mechanical properties but require more elongation to deliver the same force. [19] Masoud et al. distinguished specifically between thermoplastic and thermoset elastomeric chains. They obtained one of each from AO and ORMCO. Similar to Mirhashemi, they concluded that the thermoset chains decayed less than the thermoplastic and this led them to suggest that a clear distinction be made between the two. [20] A study by Kardach et al. came to a similar conclusion. [21]

1.3.3 The Effect of Manufacturing

Elastomeric chains can be manufactured either by injection molding or die cut stamping. Bousquet et al. compared both types of elastomers from AO in a split mouth design in vivo. They found that there was no statistically significant difference over the 3-week period and the mean remaining force of about 150 g was considered clinically adequate for canine retraction. [22] Previously Hershey and Reynolds, in an in vitro setting, found that injection molded power chains showed more force decay than die cut stamped ones. [15]

Recently with improved technology Cheng et al. set out to develop a surface treatment utilizing nanoimprinting for elastomeric chains to alleviate their shortcomings. Reduction of elasticity is due mainly to water absorption as well as surface discoloration and staining resulting from food and beverages. Convex nanopillars were fabricated on the surface of orthodontic power chains using an anodization process. This resulted in a larger contact angle after surface treatment altering the chain from hydrophilic to hydrophobic. The water absorption before surface treatment was approximately 4% whereas after treatment the rate varied from 2%-4%. They did not however study the effect on force decay which limits the clinical applicability of this study. [23]

1.3.4 The Effect of the Environment on Force Decay

De Genova tested the effects of thermal cycling on force decay. He discovered that the cycled group (15-37^{o}C) had significantly less force loss after 3 weeks than did the static temperature group of 37^{o}C. This difference was reported as only 7-10 g. [24]

Both Von Fraunhofer and Ramazanzadeh looked at the effects of topical fluoride on force delivery. They both concluded that daily use NaF does not affect the force delivery properties under conventional orthodontic forces. [25] [26]

Behnaz studied the impact of agents in whitening toothpastes and mouthwash on the force delivery of elastomeric chains. They concluded that regular toothpastes have less adverse effect on chains when compared to whitening toothpastes and that regular Crest showed the least impact on chains when compared to Sensodyne toothpastes. [27] For the mouthwash study they concluded that NaF and whitening mouthwash could cause force decay with the whitening product producing a more weakening effect. [28]

Teixeira evaluated the effect of pH on elastomeric chains. They immersed elastomeric chains in light Coke®, phosphoric acid, citric acid, and artificial saliva. Similar to other findings the most significant difference occurred within the first 24 hours, but the immersion treatments caused no statistically significant difference in force when compared to artificial saliva. [29] Nattrass et al. found the opposite effect with Coke® in that it resulted in an increased decay in force levels while Ferriter et al. found that an acidic fluoride environment reduced the level of force decay. [30, 31]

1.3.5 The effect of Sterilization on Force Decay

Jeffries et al studied the effect sterilization with a 2% alkaline glutaraldehyde solution would have on elastic properties of elastomeric chains. Due to the heat sensitive nature of elastomeric chains traditional sterilization procedures are not possible. They concluded that glutaraldehyde could be used as an effective and convenient approach to sterilize our elastomeric chains. (32)

Pithon et al considered the cytotoxicity of elastomeric chains after sterilization by different methods. Given that elastomeric chains are very susceptible to cross contamination and regularly used in orthodontics this is an important topic. They investigated seven methods of sterilization: alcohol 70; autoclave; glutaraldehyde; microwave; ultraviolet; ethylene oxide and gamma rays. They found that sterilization of elastics with ultraviolet, ethylene oxide and gamma rays does not alter their cytotoxicity whereas alcohol 70, autoclaving, glutaraldehyde and microwaving increased their cytotoxicity. One major downfall of this study is that they did not evaluate the mechanical effects of sterilization. Ultraviolet was shown to be the simplest and most accessible method and presumably doesn't affect the physical properties. (33)

1.3.6 The Effect of Storage Media on Force Decay

Ash and Kikolai in 1978 examined the differences in performance of elastomeric chains in vitro. They collected data for both in air and water. They discovered similar relaxation patterns in both but after 30 minutes of continuous loading the chains exposed to a wet environment exhibited significantly more force decay than those exposed to air only. (34) Similarly both Kuster et al. and Wong showed more force decay in chains placed in vivo compared to chains stored in air. (35) (16)

Many different formulas of artificial saliva have been used in power chain studies. When comparing the effects of artificial saliva on force decay with water there is some disagreement in the literature. Von Fraunhofer et al showed that chains in artificial saliva required more stretching to reach the required force after immersion as compared to distilled water. (25) Whereas Andreasen and Bishara reported that there was no statistically significant difference between the different mediums. (4) Baty et al. came to a similar conclusion. (36)

1.3.7 The Effect of Pre-Stretching on Force Decay

Kim et al looked at the effect of prestretching on time dependent force decay. They tested clear closed Ormco elastomeric chain comparing a study group being prestretched to 100% of initial length with a non-stretched control group. The prestretched group resulted in a significantly lower initial force than the controls but after 1-hour similar results were obtained in both. The rates and patterns from 1 hour to 4 weeks were very similar which led to the overall conclusion that the value of prestretching is questionable. (37) Baty et al in their literature review concluded that the benefits were small and probably not clinically significant given that the technique resulted in an increase in residual force at 3 weeks of approximately 5%. With a 50% to 75% overall reduction in force a 5% difference is probably of no clinical significance. (36) Halimi et al. and Yagura et al. came to a similar conclusion in their systemic review after looking at multiple studies. (38) (12)

1.3.8 The Effect of Different Ligation Designs on Force Decay

Different design mechanisms for canine retraction and associated force decay was evaluated by Balhoff et al. for four different companies using three different designs. Mechanism one was a 6-5-3 ligating each loop over each bracket. Mechanism two was a chain loop: chain stretched from first molar hook looping around the canine hook and attaching back to the molar hook bypassing the premolar hook. Mechanism three was 6-3 stretching chain from first molar hook to canine hook bypassing the premolar. For all companies the 6-3 design had the smallest mean percentage force decay suggesting that this design is the most efficient means of closing extraction spaces when using elastomeric chains. The chain loop with ten units demonstrated excessive levels of force. More loops were suggested. [39]

1.4 The Effect of Pigmentation

The question of the mechanical effects of fillers in the elastomers in the form of color pigments has been questioned in the past. Williams et al. discovered that when grey colored chains were compared to tooth colored or white chains that the grey chains tended to show less force degradation over time and that the tooth colored chains initially had much larger force values. [40]

Baty et al. compared four different colors by three different manufactures that were stored in air, water, and artificial saliva. At time 0,1,4, and 24 hours, and weeks 1 to 3 the amount of distraction needed to deliver both 150 g and 300 g was measured. They found that all chains were initially able to generate acceptable forces. In general, it took 3 mm of stretch to produce 150 g and 7 mm to produce 300 g. After 24 hours the amount of distraction needed to produce 150 g and 300 g increased substantially and this varied among the companies. In general, there was little difference between the colored chains of a particular manufacture to the grey chain of that manufacturer. There was one exception to this finding. Ormco purple and green chains needed to be stretched more to reach the desired force and had a 15 % and 21 % change at 3 weeks vs an 8 % change for grey and pink. [41]

Renick et al. used the differences in glass transition temperatures to determine differences between three different brands (RMO, Ormco, and G&H) and three different pigments (grey, red, and purple) both before orthodontic use and after being used on a patient for 4 weeks. The force delivered by these elastomeric chains is related to their molecular structure, and insight into this structure can be obtained by measuring the glass transition temperature. The glass transition spans a range of temperatures over which the solid polymer transforms from a rigid glassy stage, experiencing only vibrational molecular movements, to a flexible rubbery state with coordinated molecular motions. The higher the temperature range over which the glass transition occurs, the more rigid is the polymer and results in generation of greater force during orthodontic treatment. They found that the RMO brand was approximately 17-25 degrees higher (more rigid) than the Ormco and G&H elastomeric chains before orthodontic use. After orthodontic use there were no significant differences for the Ormco or RMO products and thus pigment would not be expected to alter mechanical properties. The G&H product had significant differences between pigments. Prior to use the differences were relatively small and would not be expected to affect their initial mechanical properties. However, after orthodontic use, the mean temperature was 15 degrees higher for the purple G&H chains compared with the grey and red, which suggests that the former might deliver higher forces. They do conclude that these findings should be verified with controlled measurements of clinical force delivery. [(42)]

Anthony et al. in 2014 compared force degradation of pigmented and non-pigmented chains of three manufactures. The found that the force delivery of the non-pigmented samples was significantly greater than the pigmented chains for all three manufactures initially, after 24 hours and after 21 days of stretching with the red and green chain coming in at the bottom. [(43)]

Both Macedo et al. and Wichai et al. looked at the effects of pigment on the long-term elasticity of elastomeric ligatures. Although not specifically elastomeric chains, these studies give us some information on the potential effects of pigmentation on synthetic polymers. Macedo et al. took 10 colors of ligature ties and stretched them 4 mm, the approximate diameter of a central incisor bracket. They found that similar to elastomeric chains they were not stable over time after being stretched and immersed in media. They also discovered that different colors displayed different behavior with deep pink, dark blue, blue, purple, and light pink displayed the most stable while grey, deep pink, silver, green, black and red displayed the least stability with red being at the bottom of the pack. [(44)] Wichai found significant differences among each color of each brand. They tested clear, pink and metallic ligatures and reported that generally pink exhibited the greatest force decay. They stated that the overall quality of ligatures is related to a combination of technology, technique refinement, and quality of the raw materials used during manufacturing, but this is generally withheld. Their results were similar to elastomeric chains in that they found 50 %-60 % force loss during the first 24 hours. [(45)]

1.5 Problem Statement

Since the introduction of orthodontic power chains, their level of force delivery and degradation has been extensively studied. Effects of manufacture, pH, sterilization, temperature, TS vs TP, and multiple other factors have been investigated. With the demand for esthetic colors and the advent of more effective materials there is limited information on the effect of pigmentation on the initial level of force delivery and its degradation over time.

1.6 Purpose

The primary purpose of this in vitro investigation is to assess the effect of pigmentation on the force degradation of elastomeric power chains in different chain types and manufactures. This study was performed over a period of 6 weeks in a simulated clinical scenario of canine retraction after extraction of a first premolar. This information will help identify which chain colors can most readily produce physiologic and clinically efficient force levels, for orthodontic space closure.

1.7 Hypothesis

It is hypothesized that variation in pigmentation of orthodontic power chains will result in a significant variation of force degradation within different manufacturers and chain types.

Chapter 2

2 Materials and Methods

2.1 Elastomeric Chains

The groups that were tested included closed chain donated from American Orthodontics (AO)(Sheboygan Wisc, USA), Ormco (Orange California, USA), and Rocky Mountain Orthodontics (RMO) (Denver Colorado, USA). AO and Ormco are supplied in both thermoplastic (TP) and thermoset (TS) forms while Rocky Mountain Orthodontics is supplied exclusively in TS. Hence, five groups were selected for evaluation:

1. American Orthodontics thermoplastic power chains (ATP)
    - Blue = ATPB
    - Red = ATPR
    - Yellow = ATPY
    - Clear = ATPC
    - Grey = ATPG
2. American Orthodontics thermoset power chains (ATS)
    - Clear = ATSC
    - Grey = ATSG
3. Ormco thermoplastic power chains (OTP)
    - Blue = OTPB
    - Red = OTPR
    - Yellow = OTPY

- Silver = OTPG

4. Ormco thermoset power chains (OTS)

- Clear = OTSC
- Grey = OTSG

5. Rocky Mountain Orthodontics thermoset power chains (RTS)

- Blue = RTSB
- Red = RTSR
- Yellow = RTSY
- Clear = RTSC
- Grey = RTSG

ATP chain was obtained in five colors, ATS chain in two colors, OTP in four colors, OTS in two colors, and RTS elastomeric chains in five colors. The TP chains were obtained in red, yellow, blue, grey, and clear except for OTP which is not manufactured in clear. ATS and OTS closed chains are only available in clear and grey while RTS was ordered in red, yellow, blue, grey, and clear. The choice of colors was based on selecting the three primary colors which conceivably could be used to produce the other colors. Clear and grey were selected as they are commonly selected as the neutral colors and the colors commonly provided in the TS form. This results in a total of 18 different groups of elastomeric chains being tested (Figure 1). Ten samples of each chain were prepared for a total of 180 samples. When requesting chain, the companies were asked to provide the most recently manufactured chain to date so that expiry date would not be of concern. The manufactured dates were within a few months of one another. Once received, the chains were stored away from light and extreme humidity in sealed bags in a cardboard box until removed for testing. The chains were tested within one month of being received. The full list of chains and associated catalogue numbers are listed in Table 1.

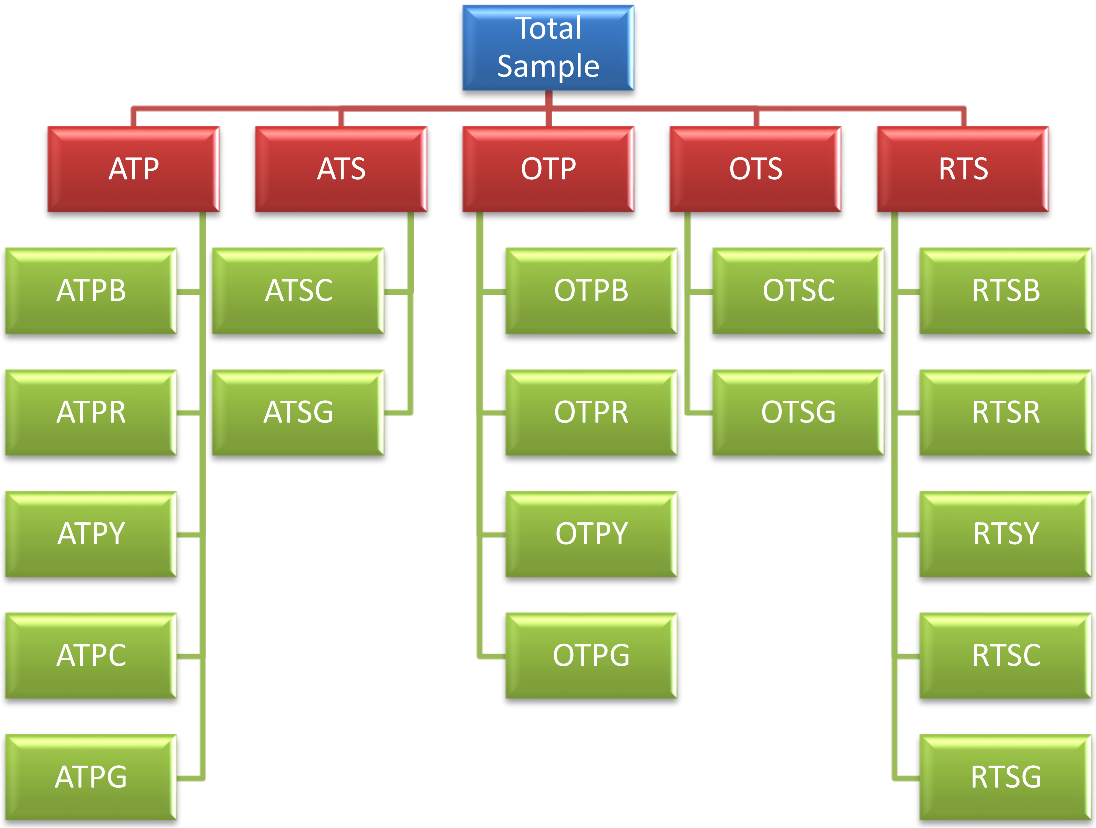


Figure 1: Total Sample comprised of 18 groups

Manufacturer	Color	Catalogue Number	Thermoplastic/Thermoset
Rocky Mountain Orthodontics	Grey	J00166	Thermoset
	Clear	J00120	Thermoset
	Red	J00231	Thermoset
	Yellow	J00267	Thermoset
	Blue	J00223	Thermoset
American Orthodontics	Grey	854-231	Thermoplastic
	Clear	854-235	Thermoplastic
	Red	854-280	Thermoplastic
	Yellow	854-340	Thermoplastic
	Blue	854-308	Thermoplastic
	Memory Grey	854-252	Thermoset
	Memory Clear	854-255	Thermoset
Ormco	Silver	639-0064	Thermoplastic
	Red	639-0044	Thermoplastic
	Yellow	639-0047	Thermoplastic
	Blue	639-0045	Thermoplastic
	Generation II Grey	639-0001	Thermoset
	Generation II Clear	639-0002	Thermoset

Table 1: Investigated Power Chains

2.2 Model Fabrication

A standard maxillary dentoform arch was impressed and poured up in orthodontic stone. The model was sectioned to one half arch and the first premolar was ground away to simulate a first premolar extraction case. 3M (3M Unitek Orthodontic Products, 2724 South Peck

Road, Monrovia, CA, USA) 022 APC Victory brackets were bonded to the teeth. This model was then sent off to a local lab (Caley Orthodontic laboratory, Waterloo ON, Canada) for scanning and duplication with a 3D printed model. Models were printed using Formlabs 3D printer (Form 2 Model, Somerville MA, USA) and Grey Resin (RS-F2-GPGR-04) from the same company (Figure 2).

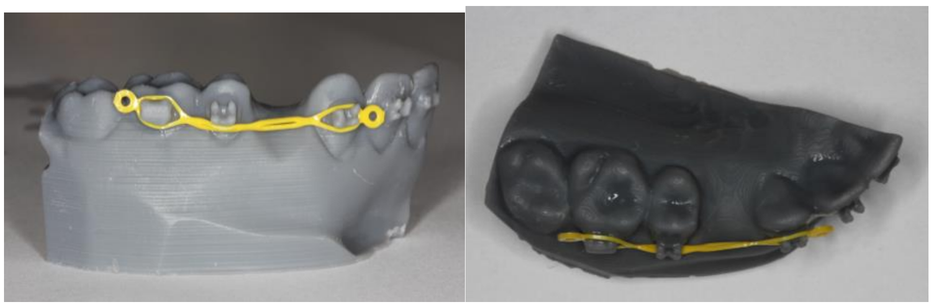


Figure 2: 3D printed model with power chain stretched from canine to first molar

2.3 Testing Conditions and Data Recording

Before the sections were cut from the spools of chain, 12 units of chain were discarded as there was evidence during the pilot study that these end samples tested outside of the norm in each group. It was hypothesized that this end chain segment could have been affected in some way during the processing or packaging stage. This is just conjecture and needs to be confirmed.

A 4-unit section of each chain is needed to stretch from canine to first molar on the dentoform model [39]. A 6-unit section of each chain was cut immediately before testing. This allowed for one extra unit on each end for placement and removal to avoid damage to the functional portion of the chain on cutting, placement and removal.

Before the chain was placed on the prepared 3D models each section of chain was tested on a Universal Instron Machine (Instron Model #3345; Norwood MA, USA) with a 10 N load cell. The functional 4-

unit section was stretched 25mm at a crosshead speed of 50mm/min to measure the initial level of force (Figure 3) (25 mm was the distance measured on the model from center of the canine to center of the first molar). The chain was attached to 3mm thick S hooks that were sufficiently strong enough to securely hold the chain and a similar width to a canine or molar bracket. The points of the S hooks were ground to a dull point and polished to a high shine to aid in placement of the chain on the hook and to avoid any undue damage to the chain. After this initial reading, the chains were placed on the correspondingly numbered 3D printed model and immersed in distilled water. The models were organized in their respective groups by placing them in one of 18 plastic containers filled with distilled water that were labeled listing the company, color, and type. Each plastic container had one elastomeric chain group to avoid contamination from chemicals released in the water and to aid in organization.

The containers were placed in an incubator (Great Lakes model dryer #131400, Tonawanda NY, USA) and maintained at 37^{0}C. The chains were removed as required for testing at 1 hour (T1), 24 hours (T2), 1 week (T3), 2 week (T4),4 week (T5) and 6 week (T6), and remaining force levels were measured. Care was taken to ensure undue damage was not inflicted on the chain during removal and insertion. After each set of measurements, the distilled water was discarded, and the models were immersed in fresh distilled water.

A. **B.** **C.** **D.**

Figure 3: Instron testing machine, **A**. Frontal view of power chain mounting hooks, **B**. 10 N Instron load cell, **C**. Great Lakes model dryer, **D**.

2.4 Pilot Study

Grey thermoplastic chain from American Orthodontics (ATOG) and grey thermoset chain from RMO (RTSG) were selected to cover both TS and TP chains. Testing was performed using the above specifications and the study was run for 6 weeks. From this data a power study calculation was performed to determine sample size. The alpha value was set at 0.05 and the beta value at 0.8. Standard deviations of 0.92 N (AO) and 0.12 N (RMO) were used since they were the highest values obtained for each company. The value for significant difference was set at 1 N which was justified based on the clinical significance of 15-20% of a mean measurement of 6.8 N. Given these parameters a sample size of 9 was calculated but it was decided to use 10 to allow an extra specimen per group in case of damage.

2.5 Data Analysis

All recorded data was compiled into the statistical software program SPSS version 24.0 (SPSS, Inc., Chicago, IL, USA). Descriptive statistical information, including mean and standard deviations (SD) was calculated for each chain group at every measured time point. Normality and lack of significant outliers was confirmed with histograms and boxplots. A 2-way Mixed Analysis of Variance (ANOVA) showed a statistically significant interaction between chain group and timepoint on force levels ($p<0.001$). After confirmation of this interaction, a One-Way ANOVA was utilized to compare force levels between chain groups at each timepoint, followed by a Tukey multiple comparison test. A repeated measures ANOVA was also utilized to determine differences in force level over time within each chain group, followed by pairwise comparisons with a Bonferroni adjustment. Since previous research literature has shown differences in force levels and decay over time between thermoset and thermoplastic power chains, all statistical tests were done separately for each chain type. Statistical significance was set as $p<0.05$.

Chapter 3

3 Results

3.1 Comparison of Thermoplastic Force Levels

There were significant differences in force levels between groups at all time points tested (p<0.001). There were also significant differences in force levels between time points within all the chain groups (p<0.001). The pairwise comparisons with each chain manufacturer are described below.

3.1.1 American Orthodontics TP

At the initial timepoint of T0, ATPY (7.4 N) delivered significantly higher force levels than all other ATP chains except ATPG (p<0.001) (Table 2). ATPR (6.7 N) delivered the lowest force values at this timepoint (p<0.05). At T1, ATPR (4.3 N) maintained significantly lower force levels than all other ATP chains at this time point (p<0.005). A trend of ATPR and ATPB exhibiting significantly lower force levels than ATPY, ATPG and ATPC was noted from T2 to T6(p<0.05). At the final timepoint of T6 ATPB and ATPR each delivered 1.3 N of force, which was significantly lower than the 1.5 N of force delivered by ATPY, ATPC and ATPG (p<0.05). These results are presented graphically in Appendix G.

All timepoints within each chain group were significantly different except ATPR, ARPY, ATPG and ATPC between timepoints T4-T5 and between T5-T6. ATPR was also not significantly different at T3-T4. After one hour the ATP groups delivered 62-65% of the original T0 force levels (Table 3). At T2 and T3 the drop-in average force levels was still substantial at 32% and 23% of the initial force delivery, respectively. From this point on force decay leveled out and settled at 19-21% at T6 depending on the group. Figure 4 displays the force decay for all TP chains combined. Individual force decay graphs for each chain can be found in Appendix D.

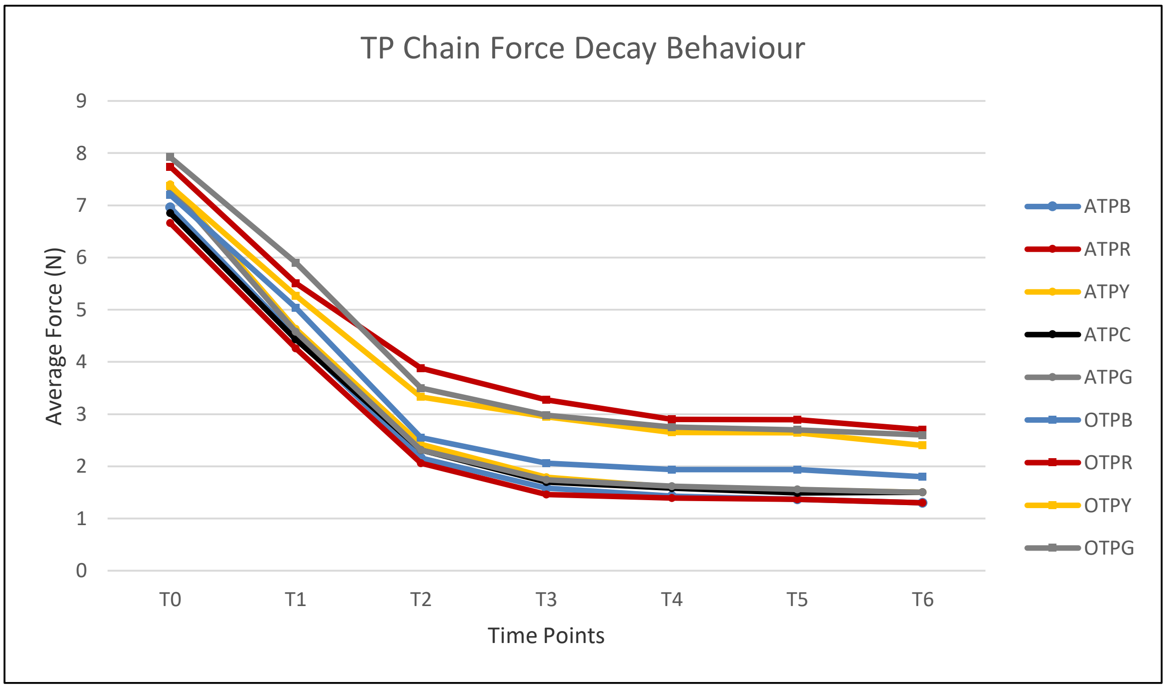


Figure 4. **Thermoplastic Chain Decay Over Time**

3.1.2 Ormco TP

Comparison of OTP groups at timepoint T0 showed that OTPR (7.7 N) and OTPG (7.9 N) had significantly higher force levels to start than OTPB (7.2 N) and OTPY (7.4 N) ($p<0.001$) (Table 2) (Appendix G). After one hour of activation (T1) OTPG (5.9 N) maintained a significantly higher force level than all other OTP groups ($p<0.001$), while OTPB (5.0 N) maintained the lowest ($p<0.001$). From T2-T6 the same general order was maintained with OTPR exhibiting significantly higher force levels than all other groups (p<0.001), OTPB significantly lower than all the other groups (p<0.001) and OTPY and OTPG statistically equal and in between (p<0.001). At 6-weeks (T6), the final force levels delivered were 2.7 N for OTPR and 1.8 N for OTPB.

All time points exhibited significant differences within each chain group except for OTPB between T3-T4, OTPR at T4-T5/T5-T6, and OTPY and OTPG at T4-T5. At T1 the OTP group dropped to 70%-74% of its initial force delivery on average, followed by 35%-50% at T2 and 29%-42% at T3 (Table 4). From T4-T6 a leveling off occurred in the OTP groups finishing off with 25%-33% remaining at T6. Individual force decay graph for each chain can be found in Appendix E.

3.2 Comparison Thermoset Force Levels

There were significant differences in force levels between groups at all time points tested (p<0.001). There were also significant differences in force levels between time points within all the chain groups (p<0.001). The pairwise comparisons with each chain manufacturer are described below.

3.2.1 American Orthodontics TS

At T0, ATSC (6.5 N) delivered significantly higher force levels than ATSG (6.1 N) (p<0.001) (Table 2). At T1 each delivered 4.4 N of force. From T2-T6 ATSC was significantly higher than ATSG (p<0.001). At T6 ATSC delivered 2.7 N while ATSG delivered 1.1N. These results are presented graphically in Appendix H.

Comparison of force levels within each group showed significant differences at between all the timepoints except at T1 the ATS group dropped to 68% of the original T0 force levels for ATSC and to 71% for ATSG (Table 3). At T2 and T3 the drop-in force levels were still high with averages of 58% and 50% of the initial force delivery, respectively. At T4 the disparity between ATSG and ATSC began to widen. ATSC maintained the highest average with 48% while ATSC dropped to 42%. This trend continued at T6 where ATSC finished with 42% while ATSG dropped to 17% of the initial force delivery (Figure 5). Individual force decay graph for each chain can be found in Appendix D.

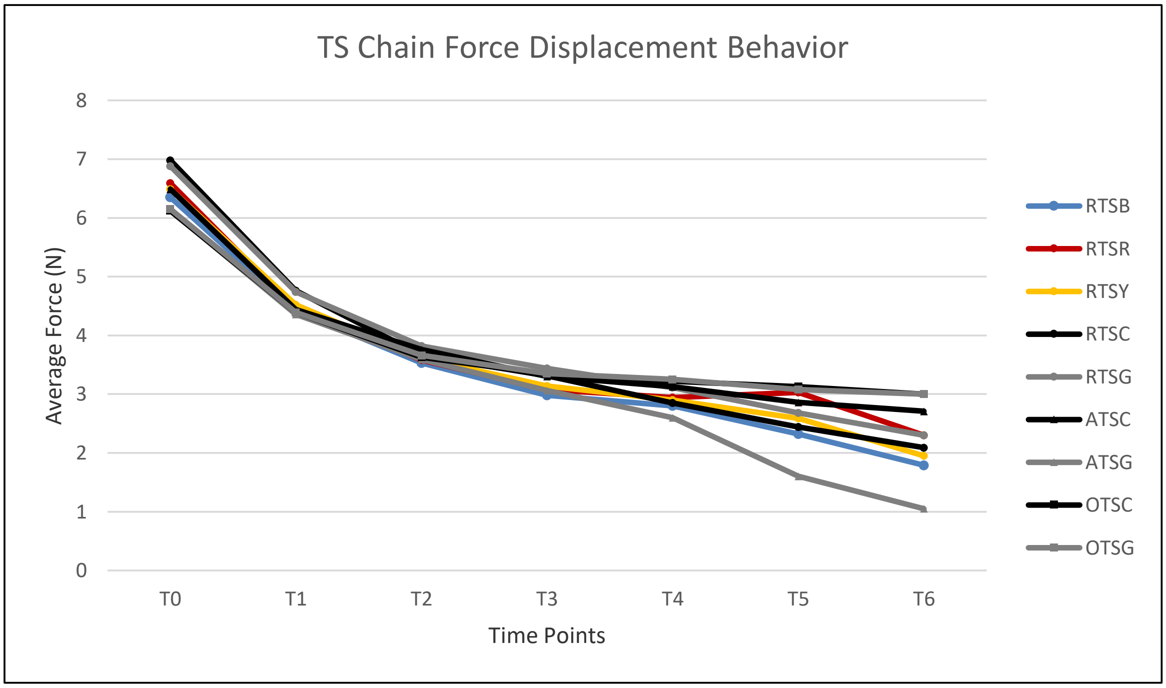


Figure 5. **Thermoset Chain Decay Over Time**

3.2.2 Ormco TS

Comparison of Ormco TS groups showed no significant differences between the OTSC and OTSG groups at all time points. At T0 OTSG delivered 6.2 N while OTSC delivered 6.1 N (Table 2). At T1 both chains decreased to 4.4 N. This trend continued where at T6 both delivered 3.0 N of force (Appendix H).

Comparison of force levels at each time point showed significant differences between all the timepoints except for OTSC at T4-T5 and T5-T6 and OTSG at T5-T6 ($p<0.005$). At T1 the OTS group dropped to 71%-

72% of its initial force delivery on average, followed by 59%-60% at T2 (Table 4). From T3-T6 a leveling off occurred with both chains finishing at 49% of the initial force delivery (Figure 5). Individual force decay graph for each chain can be found in Appendix E.

3.2.3 Rocky Mountain Orthodontics TS

At the initial timepoint of T0, RTSC (7.0 N) delivered significantly higher force levels than all other RTS chains except RTSG ($p<0.001$) (Table 2) (Appendix H). RTSB (6.4 N) delivered the lowest force value at this time point. At T1 RTSC (4.8 N) and RTSG (4.7 N) maintained their significantly higher force values than all other chains ($p<0.001$). RTSB and RTSR tied with 4.4 N for the lowest delivered force value at this time point. At T2 and T3 RTSG delivered significantly higher force levels than all the other RTS chains ($p<0.001$) while RTSB was the lowest but not statistically different from RTSR. From T4-T6 RTSB maintained this position with force levels of 3.0 N, 2.8 N, 2.3 N and 1.8 N respectively ($p<0.001$). At T6 RTSG (2.3 N) and RSTR (2.3 N) were statistically higher than all other chains ($p<0.001$).

Comparison of force levels at each time point showed significant differences between all the timepoints except RTSR between T3-T4. At T1 the RTS group dropped to 67%-70% of its initial force delivery on average, followed by 52%-56% at T2 and 47% -50% at T3 (Table 5). From T4-T6 a leveling off occurred finishing off with force decays of 28%-35% at T6 (Figure 5). Individual force decay graph for each chain can be found in Appendix F.

TS	RMO					AO		Ormco	
	Blue	Red	Yellow	Grey	Clear	Clear	Grey	Clear	Grey
Initial (T0)	6.4 (0.10)	6.6 (0.10)	6.5 (0.10)	6.9 (0.10)	7.0 (0.16)	6.5 (0.07)	6.1 (0.14)	6.1 (0.06)	6.2 (0.07)
1 Hour (T1)	4.4 (0.06)	4.4 (0.07)	4.5 (0.09)	4.7 (0.08)	4.8 (0.12)	4.4 (0.07)	4.4 (0.10)	4.4 (0.06)	4.4 (0.12)
1 Day (T2)	3.5 (0.05)	3.6 (0.06)	3.6 (0.09)	3.8 (0.06)	3.7 (0.05)	3.8 (0.07)	3.6 (0.07)	3.6 (0.07)	3.7 (0.11)
1 Week (T3)	3.0 (0.06)	3.1 (0.05)	3.1 (0.05)	3.4 (0.08)	3.3 (0.03)	3.3 (0.07)	3.1 (0.11)	3.3 (0.05)	3.4 (0.10)
2 Week (T4)	2.8 (0.05)	2.9 (0.05)	2.9 (0.05)	3.1 (0.06)	2.9 (0.05)	3.1 (0.07)	2.6 (0.12)	3.2 (0.06)	3.3 (0.09)
4 Week (T5)	2.3 (0.10)	3.0 (0.05)	2.6 (0.10)	2.7 (0.04)	2.4 (0.13)	2.9 (0.05)	1.6 (0.16)	3.1 (0.10)	3.1 (0.10)
6 Week (T6)	1.8 (0.11)	2.3 (0.08)	2.0 (0.11)	2.3 (0.07)	2.1 (0.11)	2.7 (0.07)	1.1 (0.18)	3.1 (0.05)	3.0 (0.12)

TP	AO					Ormco			
	Blue	Red	Yellow	Grey	Clear	Blue	Red	Yellow	Grey
Initial (T0)	7.0 (0.11)	6.7 (0.08)	7.4 (0.09)	7.3 (0.07)	6.9 (0.09)	7.2 (0.19)	7.7 (0.12)	7.4 (0.19)	7.9 (0.16)
1 Hour (T1)	4.5 (0.08)	4.39(0.07)	4.6 (0.08)	4.6 (0.08)	4.4 (0.08)	5.0 (0.10)	5.5 (0.11)	5.3 (0.11)	5.9 (0.09)
1 Day (T2)	2.2 (0.07)	2.2 (0.05)	2.4 (0.09)	2.3 (0.06)	2.3 (0.09)	2.6 (0.10)	3.9 (0.21)	3.3 (0.18)	3.5 (0.12)
1 Week (T3)	1.6 (0.06)	1.5 (0.05)	1.8 (0.09)	1.7 (0.05)	1.7 (0.05)	2.1 (0.08)	3.3 (0.00)	3.0 (0.11)	3.0 (0.10)
2 Week (T4)	1.4 (0.07)	1.4 (0.07)	1.6 (0.05)	1.6 (0.04)	1.6 (0.04)	1.9 (0.07)	2.9 (0.15)	2.7 (0.12)	2.8 (0.10)
4 Week (T5)	1.4 (0.08)	1.4 (0.05)	1.6 (0.05)	1.6 (0.05)	1.5 (0.06)	1.9 (0.07)	2.9 (0.15)	2.6 (0.12)	2.7 (0.12)
6 Week (T6)	1.3 (0.07)	1.3 (0.09)	1.5 (0.06)	1.5 (0.06)	1.5 (0.07)	1.8 (0.12)	2.7 (0.14)	2.4 (0.10)	2.6 (0.10)

Table 2: Average Force levels at all time points (with Standard Deviation in Parentheses) separated by TS and TP.

AO	1 Hour (T1)	1 Day (T2)	1 Week (T3)	2 Weeks (T4)	4 Weeks (T5)	6 Weeks (T6)
Blue	64	31	23	21	20	19
Red	64	31	22	21	21	20
Yellow	63	33	24	22	21	20
Grey	62	32	24	22	21	20
Clear	65	34	25	23	22	21
TS Clear	68	58	51	48	44	42
TS Grey	71	59	50	42	26	17
Average	65	39	31	28	25	23
Average TP	64	32	23	22	21	20
Average TS	70	58	50	45	35	29

Table 3. Percentage of Initial Force Remaining for AO Elastomeric Chains at Different Time Intervals

Ormco	1 Hour (T1)	1 Day (T2)	1 Week (T3)	2 Week (T4)	4 Week (T5)	6 Week (T6)
Blue	70	35	29	27	27	25
Red	71	50	42	37	37	35
Yellow	72	45	40	36	36	33
Silver	74	44	38	35	34	33
TS Clear	71	60	54	53	50	49
TS Grey	72	59	55	53	51	49
Average	72	49	43	40	39	37
Average TP	72	44	37	34	34	32
Average TS	72	59	55	53	51	49

Table 4. Percentages of Initial Force Remaining for Ormco Elastomeric Chains at Different Time Intervals

RMO	1 Hour (T1)	1 Day (T2)	1 Week (T3)	2 Week (T4)	4 Week (T5)	6 Week (T6)
RMO Blue	70	56	47	44	37	28
RMO Red	67	54	47	45	46	35
RMO Yellow	70	56	48	45	40	30
RMO Grey	69	56	50	45	39	33
RMO Clear	68	52	47	41	35	30
Average TS	69	55	48	44	39	31

Table 5. Percentages of Initial Force Remaining for RMO Elastomeric Chains at Different Time Intervals

Chapter 4

4 Discussion

Multiple methods exist to provide force for the closure of orthodontic spaces. [1] [2] [3] No method is without its limitations or issues. Elastomeric chains have long been a popular means of delivering forces for orthodontic treatment. They are known to lose effectiveness with time but are widely used due to their compatibility with soft tissues, minimal insertion and removal time, adequate force levels, and ability to dismiss compliance issues. [4] [36] [46] With the increasing demand of esthetically driven patients, the need for clinicians to provide color options for power chains has increased.

This study is unique in its aim because it is the first to compare the effects of pigmentation on both thermoset and thermoplastic power chains between different manufactures.

4.1 Methodology

Clinically this study was performed in an in vitro environment which removed the multiple uncontrollable confounding variables like pH, temperature, mastication, etc. The results here only concern themselves with the basic physical properties of the chains themselves in a controlled environment of distilled water maintained at body temperature and maintained at a set distance. These limitations need to be considered when making a clinical decision. A few in-vivo studies have been made that concluded that generally the effect of the oral environment resulted in a decline of the force values when comparing power chains exposed to in-vivo vs in-vitro conditions. [35] [22] [34]

Concerned about the importance of applying an adequate but continuous force level, this study was designed to compare the force delivery capabilities of different pigmentations of closed power chain of two chain types (thermoset and thermoplastic) from three manufacturers. The question of the mechanical effects of fillers in the elastomers in the form of color pigments has been questioned in the past. [40] [41] [42] [43] If supplied by the company, the 3 primary colors; red, yellow, and blue plus clear and grey in both TP and TS forms were tested. This selection was based on inclusion of the three primary colors while also including the most common neutral colors; grey and clear. This resulted in a total of 18 different chains.

The force values were obtained after being stretched a distance of 25 mm to simulate a first premolar extraction case as measured on a standard dentoform. The chains were attached to dentoform reproduced 3D printed models from first molar to canine as per Balhoff et al. who indicated that this is the most efficient means of closing extraction spaces with chain. [39] There is great variation of force delivery between elastomeric chains kept in wet environments and those kept in dry environments. For this reason, the power chains used in this experiment were kept in a wet medium. [16] [44] Baty et al. and Andreasen and Bisharea determined that there were no clinically important differences in the force delivery properties after storage in water or artificial saliva. [36] [4] So between measurements the stretched chains were submersed in distilled water and maintained at 37^{o}C to simulate the oral environment.

Chains were tested at time points initial, 1 hour, 1 day, 1 week, 2 weeks,4 weeks, and 6 weeks. These time points were chosen to understand the changes that occur over time between adjustment appointments while also comparing the results obtained by multiple other studies that found a drastic initial force decrease with an eventual leveling off. [46] [27] [28] [26] [29] [22] [30] [1] [31] [18] [24] [34] The 4 and 6-week time points was also chosen as an end points given that it is common today for many clinicians to place patients on 4-6-week adjustment appointments, when these chains can be replaced.

4.2 Force Levels

The phenomenon of stress relaxation is of particular interest in the case of elastomeric materials. This can be partially explained as the slippage or re-arranging of the molecules while under tension at a fixed distance. These polymers also undergo permanent deformation due to the weak molecular attraction because of the primary and secondary bonds that can be broken with force levels that exceed the limits of these bonds. (13) (14) One would expect clinically, the combination of these effects to have a detrimental effect and negate the usefulness of elastomeric power chains. The opposite appears to be the case. This combination of relaxation and deformation work to the clinician's advantage by quickly reducing the large force levels seen on the initial application of the power chain. If this rapid and dramatic decrease didn't occur, then the formation of hyalinized tissue and undermining resorption would occur and hinder tooth movement. (5)

Initially all chains delivered force levels above what is considered the upper limit of a physiologically acceptable force of 3.6 N. (10) (11) Also the TP group initially delivered higher levels of forces when compared to the TS group. Both the TP and TS groups generally dropped to acceptable levels around T2, but the TS groups were much closer to this limit. After 1 hour all chains were performing at approximately 70% of their initial force. This is in agreement with multiple other studies. (4) (16) (35) (20)In general, all chains tended to decrease at each time point, but the decrease was larger for the TP groups up to the first day when this trend continued with a gradual yet steady decline of applied force levels up to T6. Whereas the TS groups exhibited a more gradual and continuous decrease in force values while maintaining overall higher force values. At

T6 the TP group in general finished closer to the lower limit of what is considered physiologically acceptable (1.4 N). The TS groups generally finished closer to the mid-high range of the acceptable limits. This is similar to the results discovered by other studies. (20) (19) (18, 36) (22) (24) (42)

4.3 Effect of Color

In the TP group at every time point both the blue and red chains from AO were generally at the bottom of the delivered force values while red and grey from Ormco were at the top. It is interesting to see that the red pigment can be at both the high and low ends of the spectrum. The blue chains either tied or delivered the lowest value in each of the manufactures from T2-T6. Generally, the pigmented chains exhibited a lower force value than the non-pigmented chains over all time points but there was no clear pattern in forces delivered between pigments and companies.

In the TS group the same general comments can be made with the pigmented chains delivering lower force values over all time points. The clear and grey chains generally were at the top of each time point, but it must be kept in mind that the only company that makes TS pigmented chains is RMO. The blue pigmented chain again demonstrated a significant decrease in force from T0-T6. In this group the grey chain from AO was at the bottom of all the chains and showed a drastic decrease in force from T4-T6. This result was in agreement with the results shown by Mirhashemi et al. (19)

The variations found in this study regarding the different colors suggest that the different kinds of pigment used in the elastomers may change the chains behavior backing up the findings of multiple other investigators. They demonstrated differences between some brands of power chains and explained it as being the result not only of the pigment added, but also the manufacturing technique employed. The differences in the behavior of the different colors could influence the clinician's choice to provide pigmented chains to their patients. They may decide to only use non-pigmented chains in the hope of providing the most clinically efficient service to their patients. [43] [42] [40] [44] [41]

4.4 Effect of Manufacturer

In general, there was a clear distinction in the TP group with respect to manufacturer. Ormco generally delivered higher force levels at all time points when compared to AO. This effect was seen at T0 and was maintained to T6.

In the TS group at T0 Ormco generally delivered lower forces than did RMO and AO. At T1- T4 all the chains were generally equal regardless the manufacturer. At T5-T6 Ormco generally maintained its force value while the others continued to gradually drop off.

4.5 Clinical Applications

All chains except the ATSG (1.1N), ATPB (1.3N) and ATPR (1.3N) delivered within the range of effective forces (1.4N -3.6N) after the period of 6-weeks. Within our sample the OTSG (3.0 N) and OTSC (3.1 N) would allow the clinician to deliver forces at the higher end of the spectrum of acceptable levels at T6. Given the variation in forces delivered by the pigmented chains it would seem prudent to limit your choices to the non-pigmented options. When considering TS vs TP this study is in agreement with other studies and leads us to choose the TS varieties. The TS chains generally deliver a lower initial force level, albeit still greater than the upper acceptable limit. After the initial time frame, they tend to gradually decrease in force and at the 6-week time point generally deliver forces closer to the higher end of the spectrum than the TP group. TP chains tend to initially deliver forces which are much higher than TS and then generally decay and finish near the bottom of the acceptable force limit for efficient tooth movement.

4.6 Clinical Significance

The question of clinical significance as it pertains to orthodontic force levels is a difficult one to answer. With any given orthodontic movement biological variables like bone thickness, bone density, and individual physiologic cellular responses will vary. This leaves us attempting to deliver forces within a given range that we have determined to be clinically effective based upon a sample of the population. From our pilot study we set a value of 1 N to signify clinical significance. Looking at all time points the difference in absolute forces levels delivered between groups ranges from 1.6 N (OTPG 5.9 N – ATPR 4.3 N) at T1 to 2.0 N (OTSC 3.1 N – ATSG 1.1N) at T6. Clearly this is greater than our 1 N value and signifies clinical significance between chains.

4.7 Limitations of this Study

The major shortfall of this study is that the in vitro experimental design does not recreate the dynamic interactions that occur intra-orally between the oral environment and power chain. Due to the numerous thermal, chemical, and mechanical considerations that can vary from patient to patient this study did not attempt to replicate or recreate these effects. This in-vitro study provided a controlled environment that allowed a direct comparison of the effects of pigmentation, material and manufacturer.

The inability to compare the chemical composition of these materials and the pigmentations they use due to company trade secrets.

The stretch distance was not adjusted to account for natural tooth movement as would be seen in-vivo.

4.8 Strengths of this Study

The primary strength of this study was the in-vitro design that avoided multiple confounding variables. It allowed us to recreate the retraction of a canine in a first premolar extraction site. We used 3 of the most popular chain manufacturers that have a large market share and have been included in multiple studies in the past. The effects of pigments on both thermoset and thermoplastic chains was tested as they have different chemical compositions and may respond differently. To our knowledge this was the first study to conduct this comparison. We tested five different pigments, two standard and three primaries to cover a broad range of colors that which conceivably could be used to produce the other colors. The study was also carried over a 4-6-week period which is a standard time frame between standard adjustment appointments.

4.9 Suggestions for Future Research

Future force degradation studies including complete testing of all the available colors of a particular company's power chain would assist in the proper evaluation of the effects on pigmentation on performance of elastomeric power chains. Within this study it would allow us to determine if there is any association with the primary colors. Chemical analysis to determine the exact nature of the material would allow for comparison of different chain material design between companies. All future studies that evaluate the above-mentioned factors would assist the practitioner in selecting, with confidence, a power chain that would provide the most clinically efficient chain possible.

Chapter 5

5 Conclusions

The effect of pigmentation on power chains from three different manufactures in both thermoset and thermoplastic forms were tested for force degradation over a period of 6 weeks. The following conclusions were made.

1. Pigmentation plays a significant role in force levels and degradation over time, but the pattern was not consistent across all manufacturers and chain types tested.

2. Chains containing blue pigment degraded more over time than the other primary colors in the majority of manufacturers and chain types tested.

3. Most chains tested, after 6 weeks, still provided forces in the 1-3 N range which is clinically accepted to provide adequate force for orthodontic tooth movement.

References

1. Samuels RHA, Rudge SJ, Mair LH. A clinical study of space closure with nickel-titanium closed coil springs and an elastic module. American Journal of Orthodontics and Dentofacial Orthopedics. 1998;114:73-79.
2. Mohammed H, Rizk MZ, Wafaie K, Almuzian M. Effectiveness of nickel-titanium springs vs elastomeric chains in orthodontic space closure: A systematic review and meta-analysis. Orthodontics & craniofacial research. 2018;21:12-19.
3. Barlow M, Kula K. Factors influencing efficiency of sliding mechanics to close extraction space: a systematic review. Orthodontics & craniofacial research. 2008;11:65-73.
4. Andreasen George, Bishara Samir. Comparison of alastik chains with elastics involved with intra-arch molar to molar forces. The Angle Orthodontist. 1970;40:151-158.
5. Proffit WR, Fields HW, Sarver DM. Contemporary orthodontics-e-book. Elsevier Health Sciences; 2014
6. Schwarz AM. Tissue changes incidental to orthodontic tooth movement. International Journal of Orthodontia, Oral Surgery and Radiography. 1932;18:331-352.
7. Storey E. Force in orthodontics and its relation to tooth movement. Australian J Dent. 1952;56:11-18.
8. Hixon EH, Atikian H, Callow GE, McDonald HW, Tacy RJ. Optimal force, differential force, and anchorage. American Journal of Orthodontics. 1969;55:437-457.
9. Ren Y, Maltha JC, Kuijpers-Jagtman AM. Optimum force magnitude for orthodontic tooth movement: a systematic literature review. The Angle Orthodontist. 2003;73:86-92.
10. Nikolai RJ. On optimum orthodontic force theory as applied to canine retraction. American journal of orthodontics. 1975;68:290-302.
11. Boester Charlesh, Johnston Lyslee. A clinical investigation of the concepts of differential and optimal force in canine retraction. The Angle Orthodontist. 1974;44:113-119.
12. Yagura D, Baggio PE, Carreiro LS, Takahashi R. Deformation of elastomeric chains related to the amount and time of stretching. Dental press journal of orthodontics. 2013;18:136-142.
13. Billmeyer FW. Textbook of polymer science. 1971
14. Brantley WA, Eliades T. Orthodontic Materials. Thieme; 2001
15. Hershey HG, Reynolds WG. The plastic module as an orthodontic tooth-moving mechanism. American journal of orthodontics. 1975;67:554-562.
16. Wong AK. Orthodontic elastic materials. The Angle Orthodontist. 1976;46:196-205.
17. Evans KS, Wood CM, Moffitt AH et al. Sixteen-week analysis of unaltered elastomeric chain relating in-vitro force degradation with in-vivo extraction space tooth movement. American Journal of Orthodontics and Dentofacial Orthopedics. 2017;151:727-734.
18. Killiany DM, Duplessis J. Relaxation of elastomeric chains. Journal of clinical orthodontics: JCO. 1985;19:592.
19. Mirhashemi AH, Saffarshahroudi A, Sodagar A, Atai M. Force-degradation pattern of six different orthodontic elastomeric chains. Journal of dentistry (Tehran, Iran). 2012;9:204.
20. Masoud AI, Tsay TP, BeGole E, Bedran-Russo AK. Force decay evaluation of thermoplastic and thermoset elastomeric chains: A mechanical design comparison. The Angle Orthodontist. 2014;84:1026-1033.

21. Kardach H, Biedziak B, Olszewska A, Golusińska-Kardach E, Sokalski J. The mechanical strength of orthodontic elastomeric memory chains and plastic chains: An in vitro study. Advances in Clinical and Experimental Medicine. 2017;26:373-378.
22. Bousquet JA, Tuesta O, Flores-Mir C. In vivo comparison of force decay between injection molded and die-cut stamped elastomers. American Journal of Orthodontics and Dentofacial Orthopedics. 2006;129:384-389.
23. Chang JH, Hwang C-J, Kim K-H, Cha J-Y, Kim K-M, Yu HS. Effects of prestretch on stress relaxation and permanent deformation of orthodontic synthetic elastomeric chains. The Korean Journal of Orthodontics. 2018;48:384.
24. De DCG, McInnes-Ledoux P, Weinberg R, Shaye R. Force degradation of orthodontic elastomeric chains--a product comparison study. American journal of orthodontics. 1985;87:377-384.
25. Von Fraunhofer JA, Coffelt MTP, Orbell GM. The effects of artificial saliva and topical fluoride treatments on the degradation of the elastic properties of orthodontic chains. The Angle Orthodontist. 1992;62:265-274.
26. Ramazanzadeh BA, Jahanbin A, Hasanzadeh N, Eslami N. Effect of sodium fluoride mouth rinse on elastic properties of elastomeric chains. Journal of Clinical Pediatric Dentistry. 2009;34:189-192.
27. Behnaz M, Dalaie K, Hosseinpour S, Namvar F, Kazemi L. The effect of toothpastes with bleaching agents on the force decay of elastomeric orthodontic chains. European journal of dentistry. 2017;11:427.
28. Behnaz M, Namvar F, Sohrabi S, Parishanian M. Effect of Bleaching Mouthwash on Force Decay of Orthodontic Elastomeric Chains. The Journal of Contemporary Dental Practice. 2018;19:221-225.
29. Teixeira L, Pereira Bdo R, Bortoly TG, Brancher JA, Tanaka OM, Guariza-Filho O. The environmental influence of Light Coke, phosphoric acid, and citric acid on elastomeric chains. J Contemp Dent Pract. 2008;9:17-24.
30. Nattrass C, Ireland AJ, Sherriff M. The effect of environmental factors on elastomeric chain and nickel titanium coil springs. The European Journal of Orthodontics. 1998;20:169-176.
31. Ferriter JP, Meyers Jr CE, Lorton L. The effect of hydrogen ion concentration on the force-degradation rate of orthodontic polyurethane chain elastics. American Journal of Orthodontics and Dentofacial Orthopedics. 1990;98:404-410.
32. Jeffries CL, Von Fraunhofer JA. The effects of 2% alkaline gluteraldehyde solution on the elastic properties of elastomeric chain. The Angle Orthodontist. 1991;61:26-30.
33. Pithon MM, dos Santos RL, Martins FO, Romanos MTV, Araújo MT. Cytotoxicity of orthodontic elastic chain bands after sterilization by different methods. Orthodontic Waves. 2010;69:151-155.
34. Ash JL, Nikolai RJ. Relaxation of orthodontic elastomeric chains and modules in vitro and in vivo. Journal of dental research. 1978;57:685-690.
35. Kuster R, Ingervall B, Bürgin W. Laboratory and intra-oral tests of the degradation of elastic chains. The European Journal of Orthodontics. 1986;8:202-208.
36. Baty DL, Storie DJ, von Fraunhofer JA. Synthetic elastomeric chains: a literature review. Am J Orthod Dentofacial Orthop. 1994;105:536-542.
37. Kim K-H, Chung C-H, Choy K, Lee J-S, Vanarsdall RL. Effects of prestretching on force degradation of synthetic elastomeric chains. American Journal of Orthodontics and Dentofacial Orthopedics. 2005;128:477-482.
38. Halimi A, Benyahia H, Doukkali A, Azeroual M-F, Zaoui F. A systematic review of force decay in orthodontic elastomeric power chains. International orthodontics. 2012;10:223-240.
39. Balhoff DA, Shuldberg M, Hagan JL, Ballard RW, Armbruster PC. Force decay of elastomeric chains - a mechanical design and product comparison study. J Orthod. 2011;38:40-47.

40. Williams JW. Degradation of the elastic properties of orthodontic chains: a laboratory study in a simulated oral environment [dissertation]. University of Louisville; 1990.
41. Baty DL. Force displacement and dimensional stability of various colored elastomeric chains in air, distilled water and artificial saliva. 1993
42. Renick MR, Brantley WA, Beck FM, Vig KWL, Webb CS. Studies of orthodontic elastomeric modules. Part 1: Glass transition temperatures for representative pigmented products in the as-received condition and after orthodontic use. American Journal of Orthodontics and Dentofacial Orthopedics. 2004;126:337-343.
43. Antony PJ, Paulose J. An in-vitro study to compare the force degradation of pigmented and non-pigmented elastomeric chains. Indian Journal of Dental Research. 2014;25:208.
44. Macêdo Édodd, Collares FM, Leitune VCB, Samuel SMW, Fortes CBB. Pigment effect on the long term elasticity of elastomeric ligatures. Dental Press Journal of Orthodontics. 2012;17:1-6.
45. Wichai W, Anuwongnukroh N, Dechkunakorn S, Kaypetch R, Tua-ngam P. Initial Tensile and Residual Forces of Pigmented Elastomeric Ligatures from Various Brands. IOP Conference Series: Materials Science and Engineering. 2017;265:012012.
46. Patel A, Thomas B. In vivo evaluation of the force degradation characteristics of four contemporarily used elastomeric chains over a period of 6 weeks. Journal of the World Federation of Orthodontists. 2018;7:141-145.

Appendices

Appendix A: Raw Force (N) Data for RMO

Blue							
	Initial	1 hr	24 hrs	1 week	2 weeks	4 weeks	6 weeks
1	6.3	4.5	3.5	3.0	2.8	2.3	1.8
2	6.4	4.4	3.6	3.0	2.8	2.1	1.6
3	6.4	4.5	3.6	3.0	2.8	2.2	1.6
4	6.4	4.5	3.5	2.9	2.8	2.4	1.9
5	6.2	4.4	3.5	2.9	2.8	2.4	1.8
6	6.2	4.4	3.5	2.9	2.7	2.4	1.9
7	6.3	4.4	3.5	3.0	2.8	2.4	1.9
8	6.4	4.3	3.5	3.1	2.8	2.4	1.8
9	6.4	4.4	3.6	3.0	2.9	2.3	1.8
10	6.5	4.4	3.5	3.0	2.8	2.3	1.8
Red							
	Initial	1 hr	24 hrs	1 week	2 weeks	4 weeks	6 weeks
1	6.8	4.4	3.6	3.1	2.9	3.0	2.3
2	6.6	4.5	3.6	3.1	3.0	3.0	2.3
3	6.5	4.4	3.6	3.1	2.9	3.0	2.2
4	6.6	4.4	3.6	3.1	3.0	3.1	2.2
5	6.7	4.5	3.6	3.1	3.0	3.1	2.4
6	6.6	4.5	3.6	3.1	2.9	3.0	2.3
7	6.5	4.5	3.5	3.1	2.9	3.0	2.4
8	6.5	4.3	3.5	3.0	2.9	3.0	2.3
9	6.5	4.4	3.5	3.0	2.9	3.0	2.2
10	6.6	4.5	3.7	3.1	3.0	3.1	2.4
Yellow							
	Initial	1 hr	24 hrs	1 week	2 weeks	4 weeks	6 weeks
1	6.5	4.5	3.6	3.2	2.9	2.7	2.1
2	6.5	4.7	3.7	3.1	2.9	2.4	1.8
3	6.4	4.6	3.7	3.1	2.9	2.5	1.9
4	6.4	4.6	3.6	3.1	2.9	2.5	1.8
5	6.5	4.5	3.6	3.1	2.9	2.6	1.9
6	6.5	4.5	3.6	3.1	2.9	2.7	2.1
7	6.5	4.4	3.6	3.2	2.9	2.6	2.0
8	6.5	4.5	3.7	3.2	3.0	2.6	1.9
9	6.5	4.4	3.4	3.1	2.8	2.6	2.0
10	6.6	4.5	3.6	3.2	2.9	2.7	2.0
Gray							
	Initial	1 hr	24 hrs	1 week	2 weeks	4 weeks	6 weeks
1	6.9	4.7	3.8	3.4	3.1	2.6	2.2
2	6.9	4.6	3.7	3.3	3.1	2.6	2.2
3	7.0	4.7	3.9	3.5	3.1	2.7	2.3
4	6.8	4.8	3.8	3.5	3.1	2.7	2.3
5	7.0	4.7	3.8	3.4	3.1	2.7	2.4
6	6.9	4.8	3.8	3.4	3.1	2.7	2.3
7	7.0	4.9	3.8	3.4	3.2	2.7	2.4
8	6.8	4.8	3.8	3.4	3.0	2.7	2.3
9	6.8	4.7	3.9	3.5	3.2	2.7	2.3
10	6.7	4.7	3.9	3.6	3.1	2.7	2.3
Clear							
	Initial	1 hr	24 hrs	1 week	2 weeks	4 weeks	6 weeks
1	7.2	4.8	3.6	3.3	2.9	2.2	1.9
2	6.8	4.9	3.7	3.4	2.9	2.3	1.9
3	6.7	4.8	3.6	3.3	2.8	2.4	2.1
4	6.9	4.7	3.6	3.3	2.8	2.4	2.1
5	7.1	4.8	3.7	3.3	2.8	2.5	2.1
6	7.0	4.9	3.7	3.3	2.8	2.6	2.2
7	6.9	4.8	3.6	3.3	2.9	2.5	2.2
8	7.1	4.7	3.7	3.3	2.9	2.5	2.1
9	7.1	4.5	3.7	3.3	2.8	2.4	2.1
10	7.0	4.7	3.7	3.3	2.9	2.6	2.2

Appendix B: Raw Force (N) Data for AO

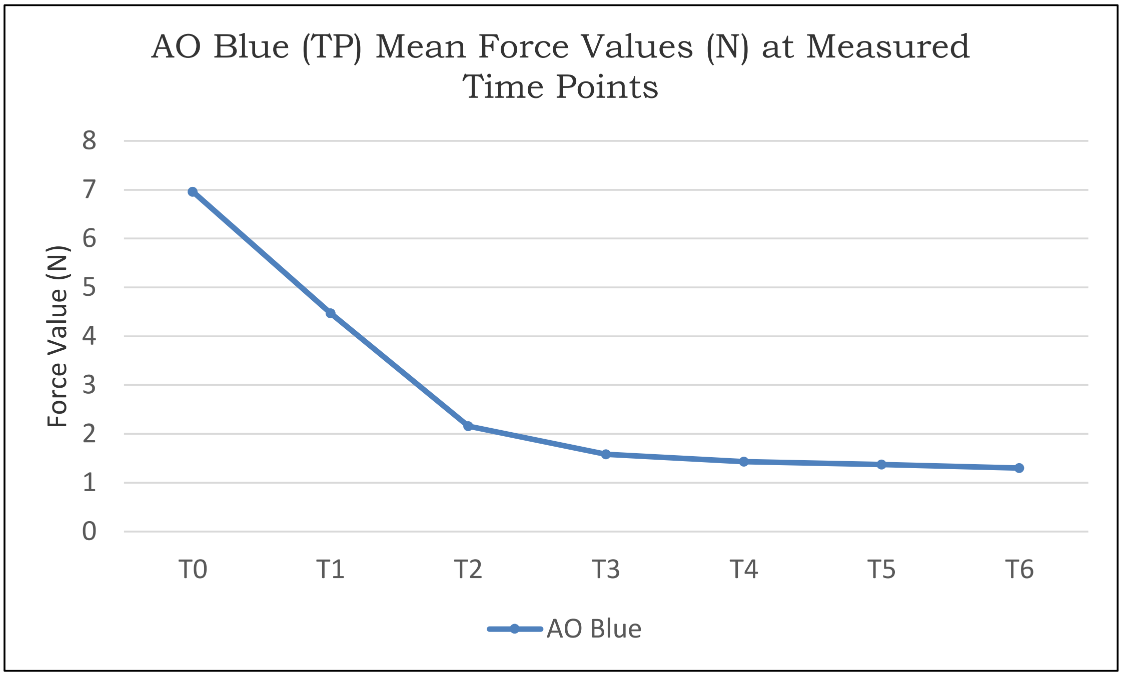
Blue							
	Initial	1 hr	24 hrs	1 week	2 weeks	4 weeks	6 weeks
1	7.1	4.4	2.2	1.6	1.5	1.4	1.3
2	6.8	4.6	2.3	1.6	1.5	1.5	1.4
3	7.1	4.6	2.2	1.7	1.4	1.4	1.3
4	7.0	4.4	2.1	1.6	1.4	1.4	1.3
5	6.9	4.5	2.1	1.6	1.4	1.3	1.2
6	6.8	4.5	2.2	1.6	1.5	1.4	1.3
7	7.0	4.5	2.1	1.5	1.4	1.4	1.2
8	7.0	4.4	2.1	1.5	1.3	1.2	1.2
9	6.9	4.4	2.1	1.5	1.4	1.3	1.2
10	7.0	4.4	2.2	1.6	1.5	1.4	1.3
Red							
	Initial	1 hr	24 hrs	1 week	2 weeks	4 weeks	6 weeks
1	6.6	4.3	2.1	1.5	1.5	1.4	1.4
2	6.7	4.4	2.1	1.5	1.5	1.4	1.4
3	6.7	4.3	2.0	1.4	1.3	1.4	1.2
4	6.7	4.2	2.1	1.5	1.4	1.3	1.4
5	6.7	4.2	2.0	1.4	1.4	1.4	1.3
6	6.8	4.3	2.1	1.5	1.4	1.4	1.4
7	6.6	4.2	2.1	1.5	1.4	1.4	1.3
8	6.7	4.2	2.0	1.4	1.3	1.3	1.2
9	6.6	4.2	2.0	1.4	1.3	1.3	1.2
10	6.5	4.3	2.1	1.5	1.4	1.4	1.4
Yellow							
	Initial	1 hr	24 hrs	1 week	2 weeks	4 weeks	6 weeks
1	7.5	4.8	2.4	1.8	1.6	1.5	1.5
2	7.5	4.6	2.4	1.7	1.6	1.6	1.5
3	7.4	4.6	2.3	1.7	1.6	1.5	1.5
4	7.5	4.6	2.5	1.8	1.6	1.6	1.5
5	7.4	4.7	2.4	1.7	1.6	1.5	1.5
6	7.4	4.7	2.6	1.9	1.7	1.6	1.6
7	7.3	4.6	2.4	1.8	1.6	1.6	1.5
8	7.2	4.5	2.3	1.7	1.5	1.5	1.4
9	7.4	4.6	2.4	1.9	1.6	1.6	1.6
10	7.4	4.6	2.5	1.9	1.6	1.5	1.5
Gray							
	Initial	1 hr	24 hrs	1 week	2 weeks	4 weeks	6 weeks
1	7.3	4.7	2.4	1.7	1.6	1.6	1.5
2	7.3	4.6	2.3	1.8	1.7	1.6	1.5
3	7.3	4.6	2.3	1.7	1.6	1.5	1.5
4	7.4	4.7	2.3	1.7	1.6	1.6	1.5
5	7.4	4.6	2.3	1.7	1.6	1.6	1.5
6	7.2	4.5	2.2	1.7	1.6	1.5	1.4
7	7.3	4.5	2.3	1.8	1.6	1.6	1.5
8	7.3	4.5	2.3	1.7	1.6	1.5	1.5
9	7.4	4.6	2.4	1.8	1.7	1.6	1.6
10	7.4	4.5	2.3	1.8	1.6	1.5	1.5
Clear							
	Initial	1 hr	24 hrs	1 week	2 weeks	4 weeks	6 weeks
1	6.8	4.6	2.3	1.7	1.6	1.6	1.5
2	6.9	4.5	2.2	1.7	1.6	1.5	1.6
3	7.0	4.4	2.3	1.7	1.6	1.5	1.4
4	6.9	4.4	2.2	1.6	1.5	1.4	1.4
5	6.7	4.4	2.4	1.7	1.6	1.5	1.5
6	6.8	4.4	2.2	1.7	1.5	1.5	1.4
7	6.8	4.5	2.4	1.7	1.6	1.4	1.5
8	6.9	4.4	2.4	1.7	1.6	1.5	1.4
9	6.8	4.3	2.4	1.7	1.6	1.5	1.5
10	6.9	4.4	2.3	1.8	1.6	1.5	1.5

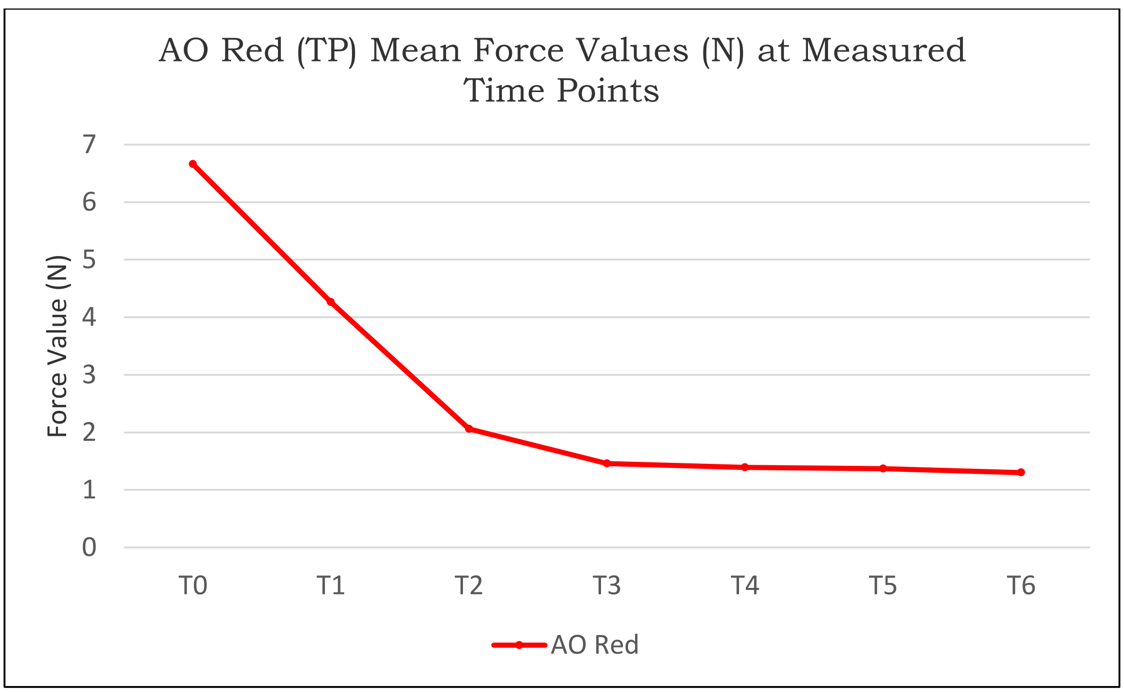
Memory Gray							
	Initial	1 hr	24 hrs	1 week	2 weeks	4 weeks	6 weeks
1	5.8	4.4	3.6	3.0	2.7	1.4	1.0
2	6.2	4.3	3.6	3.0	2.6	1.7	1.0
3	6.3	4.2	3.5	2.9	2.4	1.4	0.8
4	6.3	4.4	3.6	3.1	2.5	1.5	0.8
5	6.1	4.3	3.5	3.0	2.5	1.5	1.1
6	6.1	4.3	3.6	3.1	2.6	1.6	1.0
7	6.1	4.5	3.7	3.1	2.6	1.6	1.0
8	6.1	4.3	3.5	3.0	2.6	1.7	1.2
9	6.2	4.4	3.6	3.1	2.7	1.7	1.2
10	6.1	4.5	3.7	3.3	2.8	1.9	1.4
Memory Clear							
	Initial	1 hr	24 hrs	1 week	2 weeks	4 weeks	6 weeks
1	6.4	4.4	3.7	3.3	3.1	2.8	2.7
2	6.6	4.5	3.8	3.4	3.2	2.9	2.7
3	6.5	4.3	3.7	3.2	3.0	2.8	2.6
4	6.5	4.4	3.8	3.3	3.2	2.8	2.6
5	6.4	4.4	3.7	3.3	3.1	2.9	2.7
6	6.6	4.5	3.7	3.3	3.1	2.9	2.8
7	6.5	4.5	3.8	3.3	3.2	2.9	2.8
8	6.5	4.5	3.9	3.4	3.2	2.9	2.8
9	6.5	4.5	3.8	3.3	3.1	2.9	2.7
10	6.4	4.4	3.7	3.2	3.1	2.8	2.7

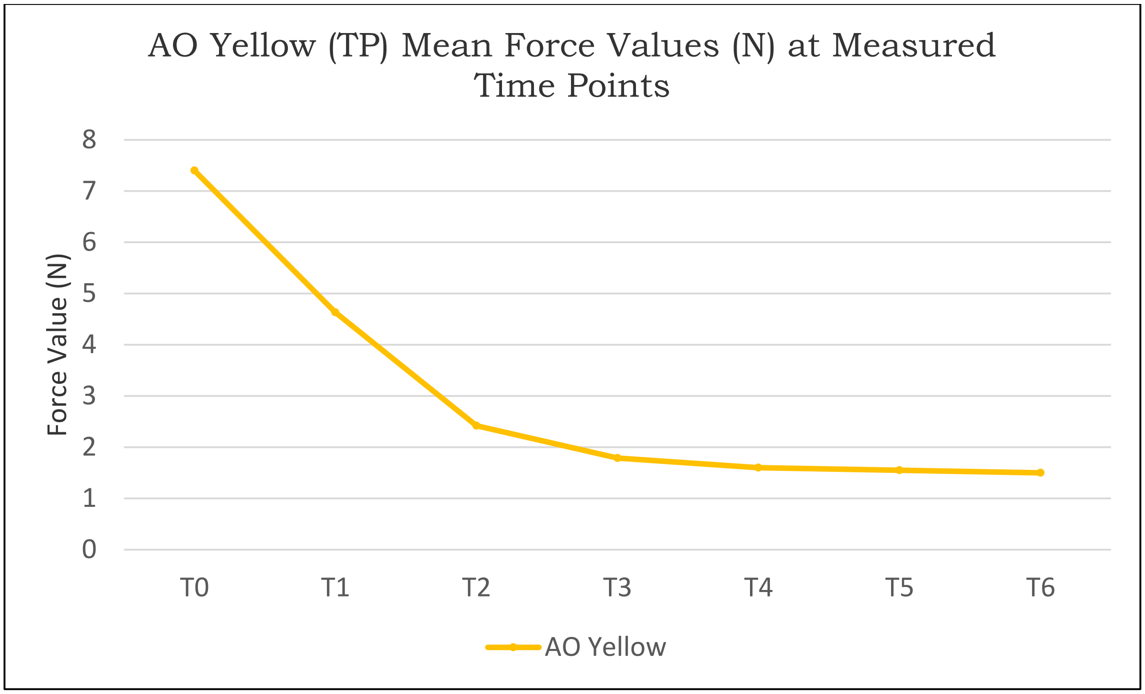
Appendix C: Raw Force (N) Data for Ormco

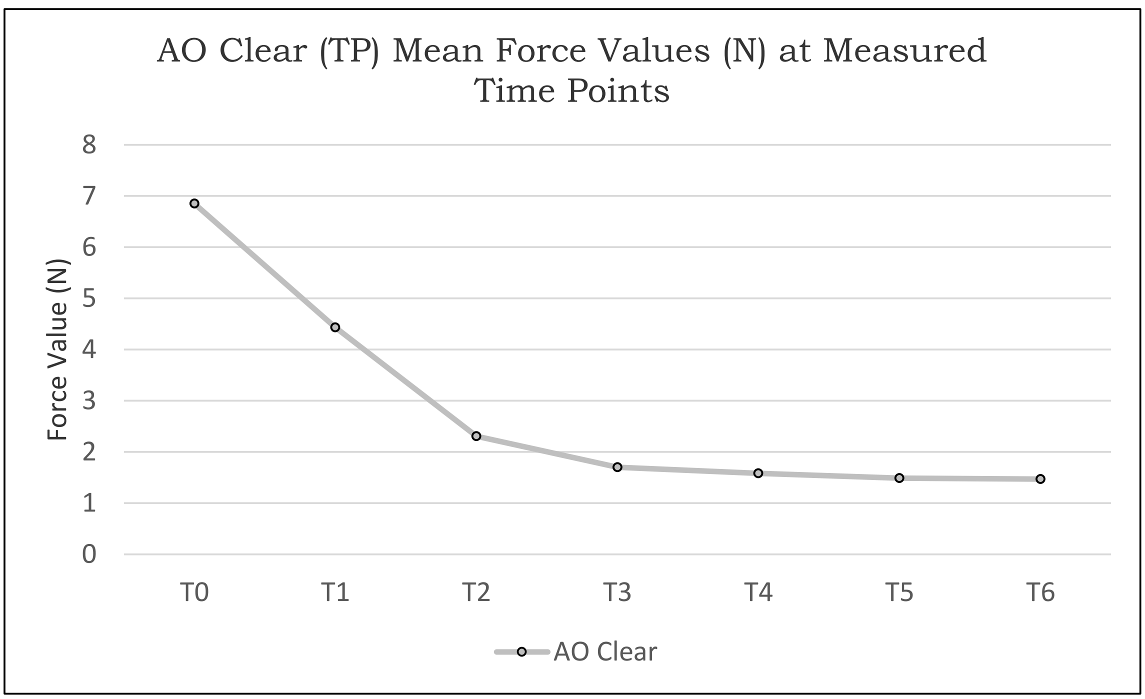
Blue							
	Initial	1 hr	24 hrs	1 week	2 weeks	4 weeks	6 weeks
1	7.4	5.0	2.5	2.0	2.0	2.0	1.7
2	7.5	4.9	2.7	2.1	2.0	2.0	1.9
3	6.9	4.9	2.4	2.0	1.9	1.9	1.7
4	7.1	5.1	2.4	1.9	1.8	1.8	1.6
5	7.0	5.1	2.6	2.1	2.0	2.0	1.9
6	7.1	5.0	2.5	2.0	1.9	1.9	1.8
7	7.3	5.1	2.6	2.1	2.0	2.0	1.8
8	7.2	5.1	2.6	2.2	1.9	1.9	1.9
9	7.4	5.2	2.6	2.1	2.0	2.0	2.0
10	7.2	5.0	2.6	2.1	1.9	1.9	1.9
Red							
	Initial	1 hr	24 hrs	1 week	2 weeks	4 weeks	6 weeks
1	7.9	5.4	4.0	3.3	3.0	3.1	2.7
2	7.8	5.6	4.2	3.3	3.1	3.0	2.8
3	7.7	5.4	3.5	3.3	2.7	2.7	2.5
4	7.8	5.4	3.7	3.3	3.0	2.9	2.8
5	7.7	5.5	3.7	3.3	2.9	2.8	2.7
6	7.8	5.6	3.9	3.3	3.0	3.1	3.0
7	7.8	5.7	4.1	3.3	3.0	2.9	2.8
8	7.5	5.6	4.0	3.3	2.7	2.8	2.6
9	7.8	5.4	3.8	3.3	2.7	2.7	2.6
10	7.6	5.5	3.9	3.3	2.9	2.9	2.8
Yellow							
	Initial	1 hr	24 hrs	1 week	2 weeks	4 weeks	6 weeks
1	7.4	5.3	3.5	3.0	2.7	2.7	2.5
2	7.5	5.3	3.6	3.0	2.8	2.8	2.5
3	7.7	5.3	3.3	2.8	2.5	2.6	2.3
4	7.4	5.3	3.5	3.0	2.7	2.7	2.5
5	7.1	5.1	3.1	2.8	2.5	2.5	2.3
6	7.2	5.2	3.3	3.0	2.7	2.7	2.5
7	7.5	5.3	3.3	3.1	2.7	2.7	2.5
8	7.4	5.1	3.0	2.8	2.5	2.4	2.3
9	7.1	5.4	3.4	3.0	2.8	2.7	2.5
10	7.4	5.4	3.3	3.0	2.6	2.6	2.5
Silver							
	Initial	1 hr	24 hrs	1 week	2 weeks	4 weeks	6 weeks
1	8.0	6.0	3.7	3.1	2.8	2.8	2.6
2	8.0	5.8	3.6	3.0	2.9	2.8	2.7
3	8.0	5.9	3.5	3.0	2.8	2.6	2.5
4	7.5	5.7	3.5	2.9	2.7	2.7	2.5
5	7.9	5.9	3.5	3.0	2.8	2.8	2.6
6	8.0	5.9	3.3	2.9	2.6	2.6	2.5
7	8.0	5.9	3.5	3.1	2.8	2.8	2.6
8	7.9	6.0	3.4	2.9	2.6	2.5	2.4
9	7.9	6.0	3.6	3.1	2.8	2.8	2.7
10	8.0	5.9	3.4	2.8	2.7	2.6	2.5
Generation II Grey							
	Initial	1 hr	24 hrs	1 week	2 weeks	4 weeks	6 weeks
1	6.1	4.3	3.7	3.3	3.2	3.2	3.0
2	6.0	4.4	3.7	3.4	3.3	3.1	3.0
3	6.2	4.3	3.6	3.2	3.1	2.9	2.7
4	6.1	4.4	3.7	3.3	3.3	3.1	3.0
5	6.2	4.3	3.5	3.3	3.2	3.0	2.9
6	6.2	4.6	3.8	3.5	3.4	3.2	3.1
7	6.2	4.5	3.8	3.5	3.3	3.2	3.1
8	6.2	4.4	3.5	3.3	3.2	3.0	2.9
9	6.2	4.2	3.6	3.3	3.2	3.0	3.0
10	6.1	4.5	3.7	3.4	3.3	3.1	3.1
Generation II Clear							
	Initial	1 hr	24 hrs	1 week	2 weeks	4 weeks	6 weeks
1	6.2	4.4	3.7	3.3	3.2	3.1	3.0
2	6.2	4.4	3.6	3.4	3.3	3.3	3.0
3	6.1	4.3	3.5	3.3	3.1	3.2	2.7
4	6.2	4.4	3.7	3.4	3.2	3.2	3.0
5	6.1	4.3	3.6	3.3	3.2	3.0	2.9
6	6.1	4.4	3.7	3.3	3.2	3.2	3.1
7	6.1	4.5	3.6	3.4	3.3	3.1	3.1
8	6.0	4.4	3.7	3.4	3.2	3.1	2.9
9	6.1	4.4	3.6	3.3	3.3	3.0	3.0
10	6.1	4.4	3.6	3.3	3.2	3.1	3.1

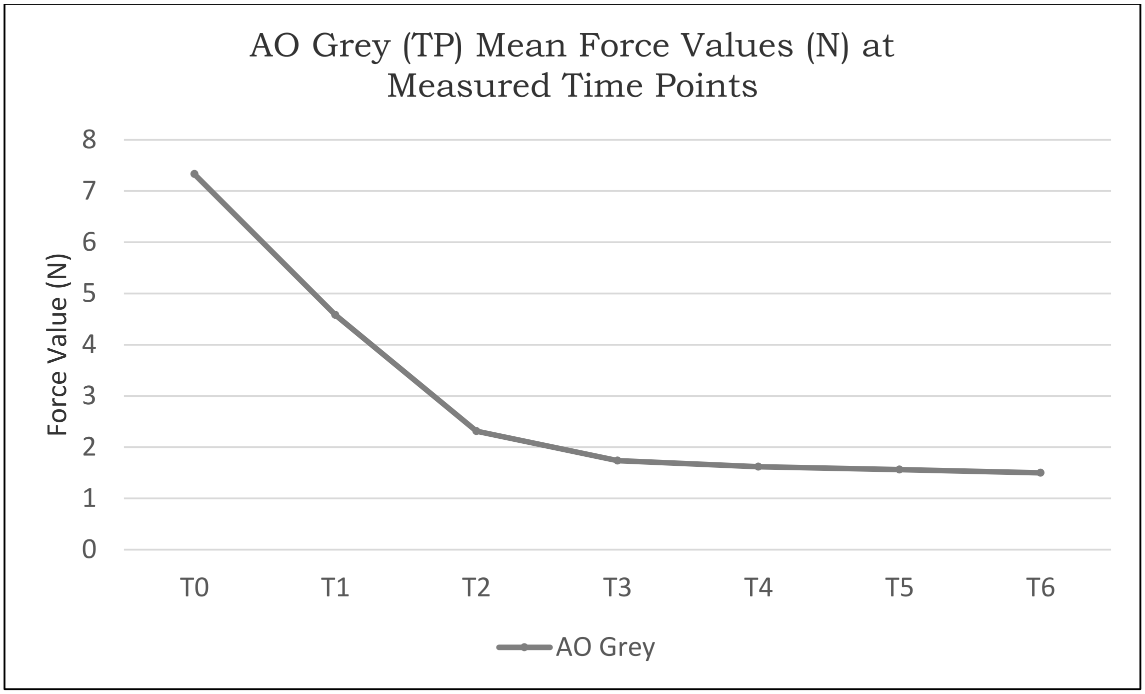
Appendix D: Force Displacement Behavior AO

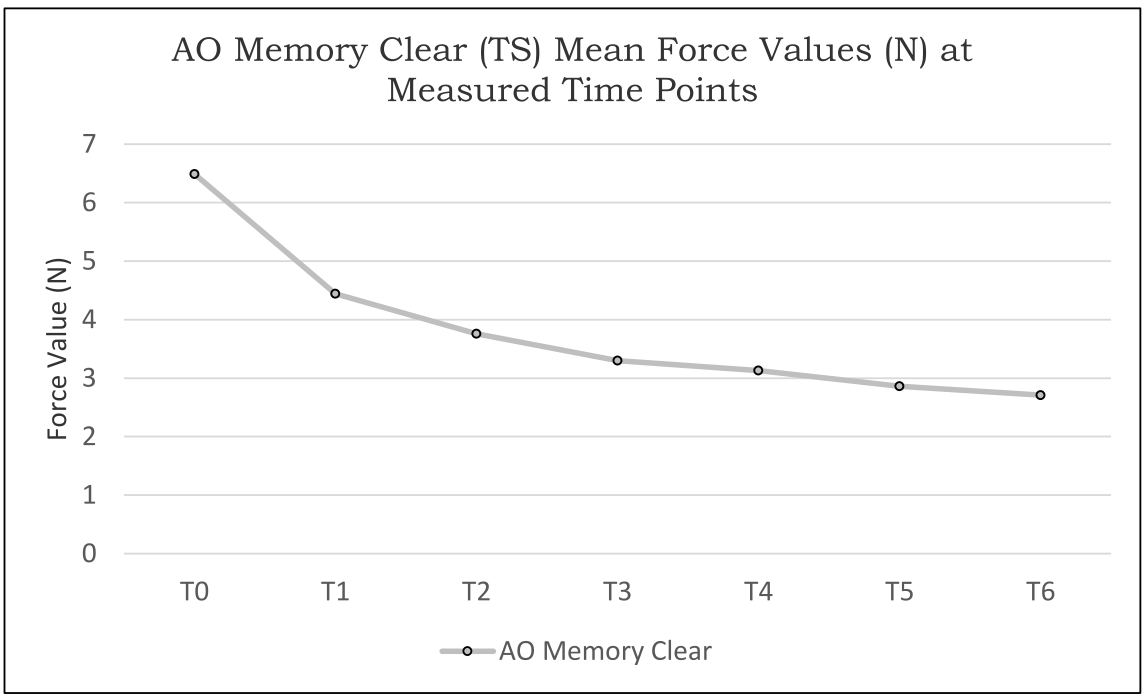


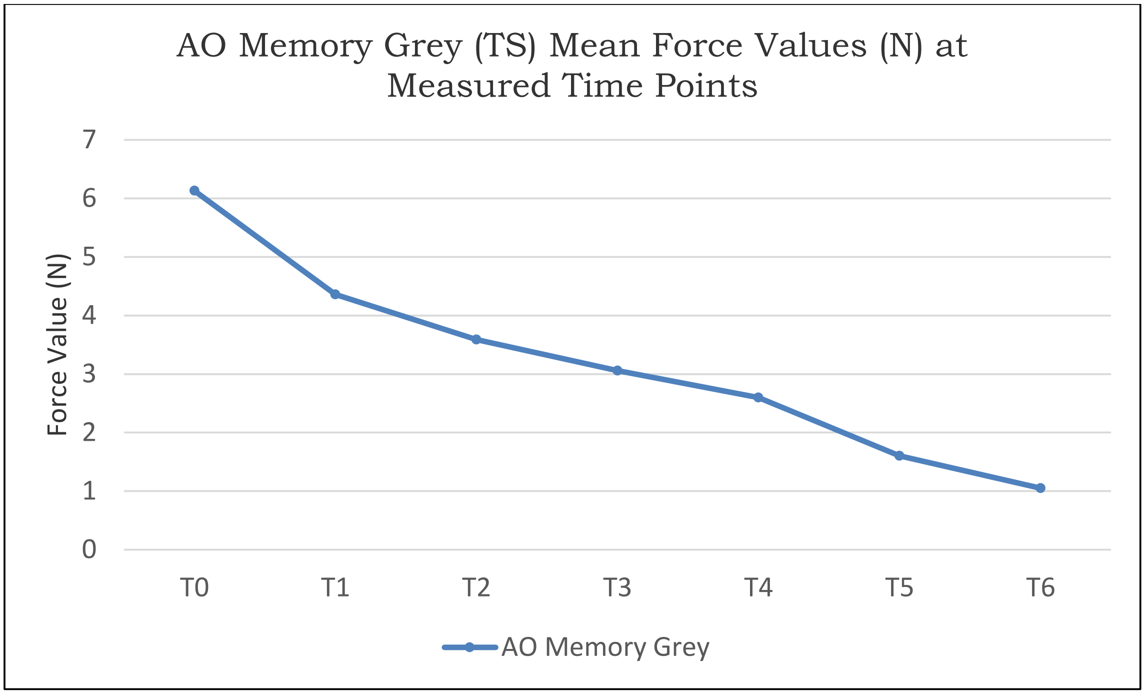



AO Yellow (TP) Mean Force Values (N) at Measured Time Points
Force Value (N)
8
7
6
5
4
3
2
1
0
T0
T1
T2
T3
T4
T5
T6
AO Yellow

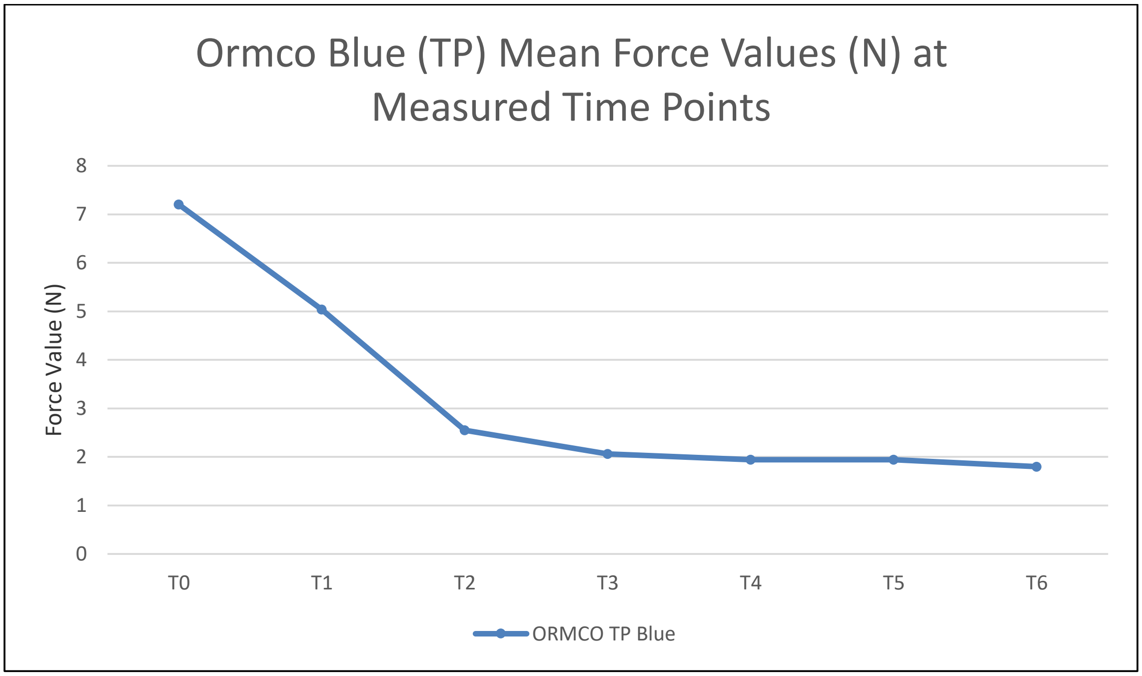

AO Clear (TP) Mean Force Values (N) at Measured Time Points
Force Value (N)
8
7
6
5
4
3
2
1
0
T0
T1
T2
T3
T4
T5
T6
AO Clear

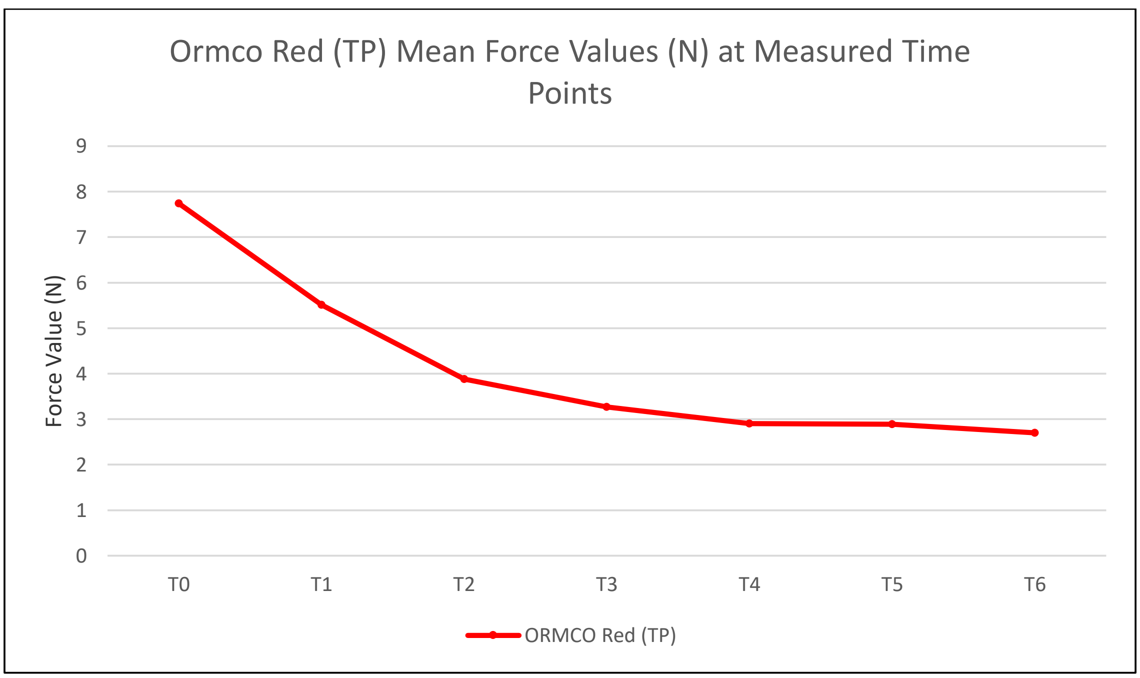

AO Grey (TP) Mean Force Values (N) at Measured Time Points
Force Value (N)
8
7
6
5
4
3
2
1
0
T0
T1
T2
T3
T4
T5
T6
AO Grey

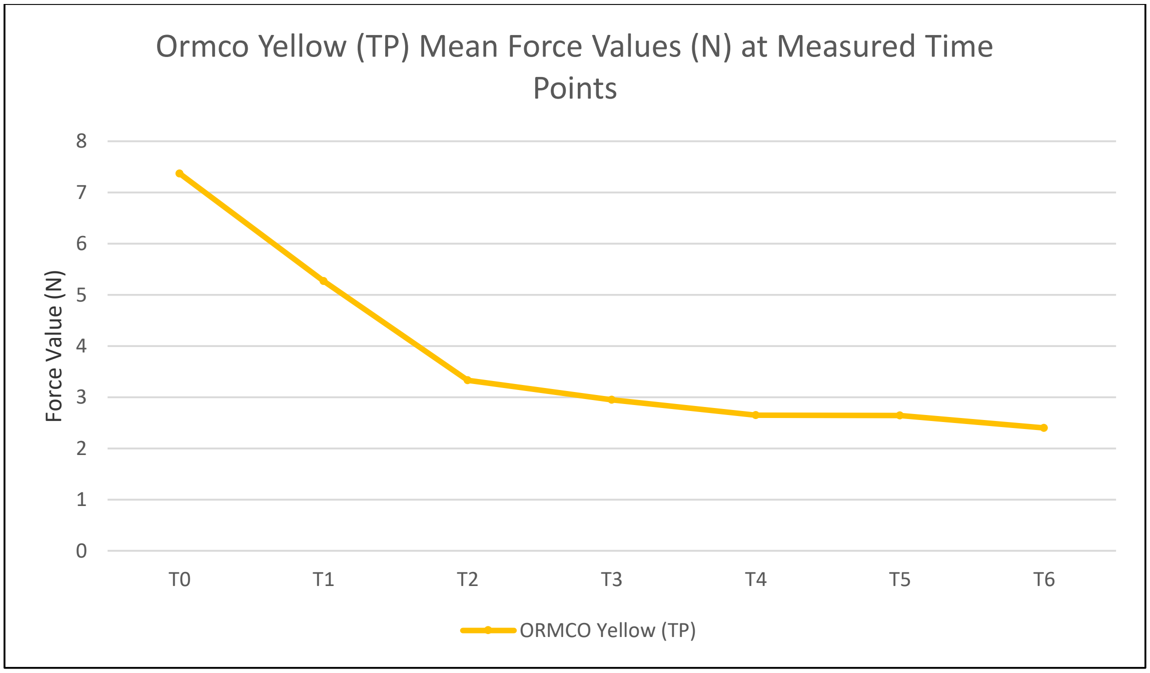

AO Memory Clear (TS) Mean Force Values (N) at Measured Time Points
Force Value (N)
7
6
5
4
3
2
1
0
T0
T1
T2
T3
T4
T5
T6
AO Memory Clear

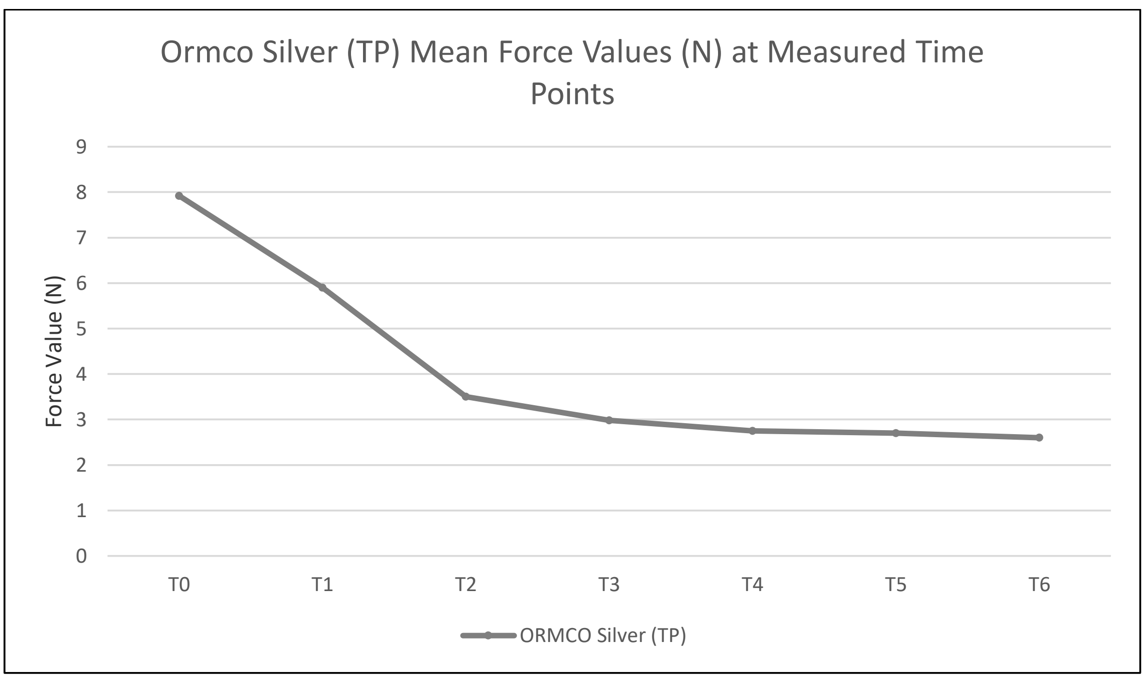

AO Memory Grey (TS) Mean Force Values (N) at Measured Time Points
Force Value (N)
7
6
5
4
3
2
1
0
T0
T1
T2
T3
T4
T5
T6
AO Memory Grey

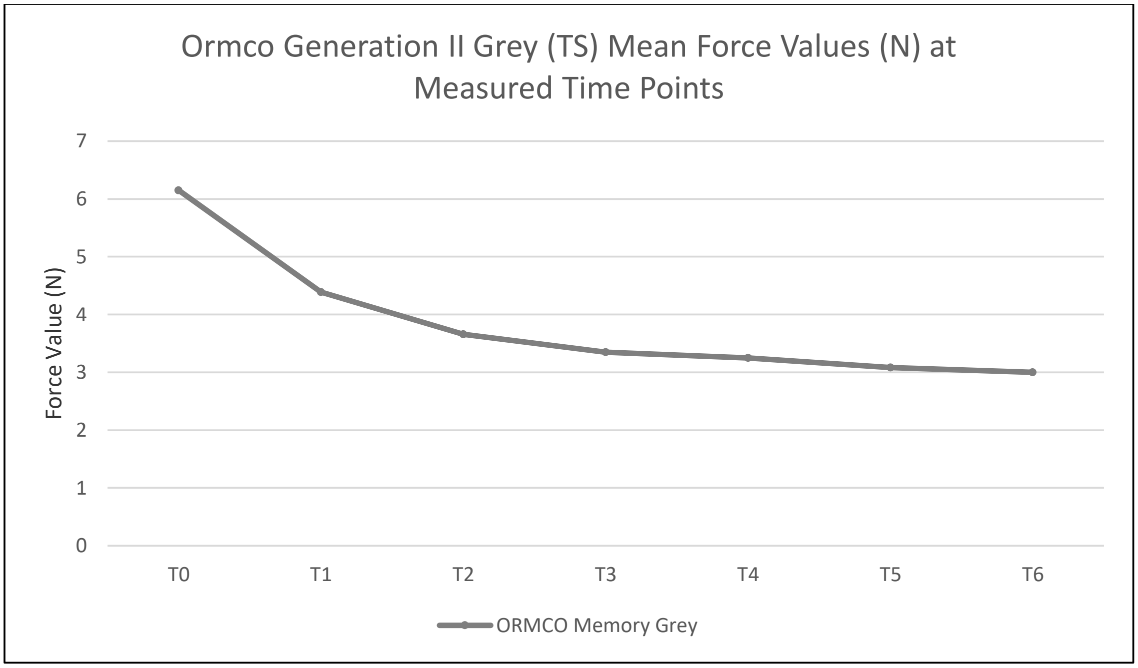
Appendix E: Force Displacement Behavior Ormco



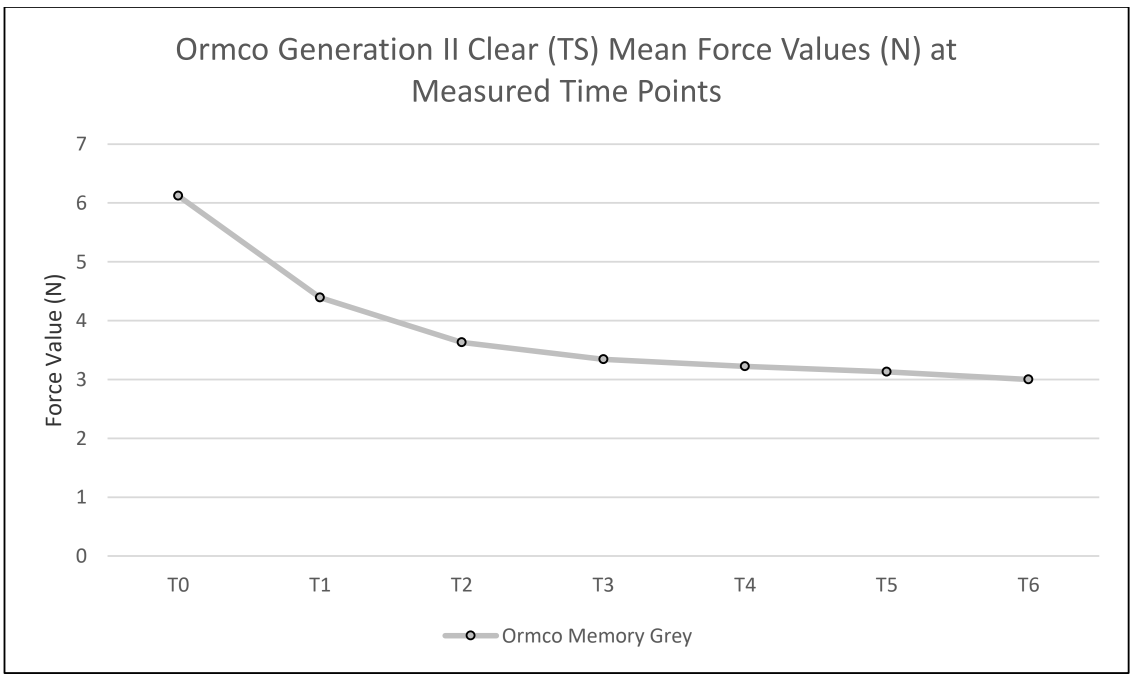



Ormco Yellow (TP) Mean Force Values (N) at Measured Time Points
Force Value (N)
8
7
6
5
4
3
2
1
0
T0
T1
T2
T3
T4
T5
T6
ORMCO Yellow (TP)


Ormco Silver (TP) Mean Force Values (N) at Measured Time Points
Force Value (N)
9
8
7
6
5
4
3
2
1
0
T0
T1
T2
T3
T4
T5
T6
ORMCO Silver (TP)

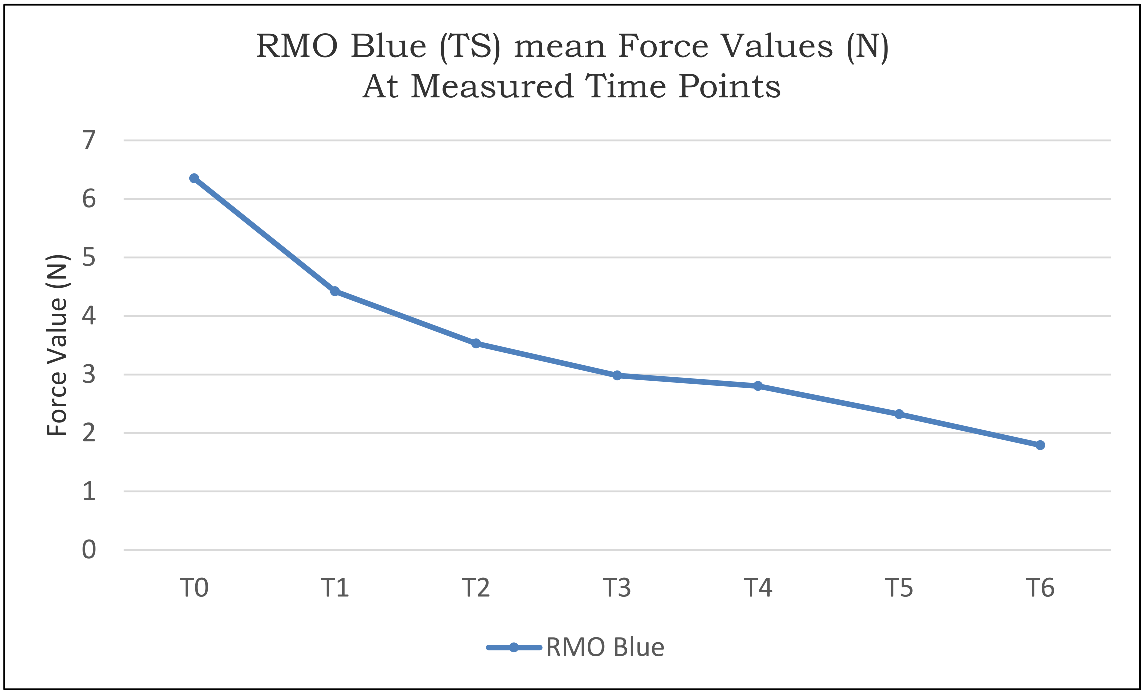


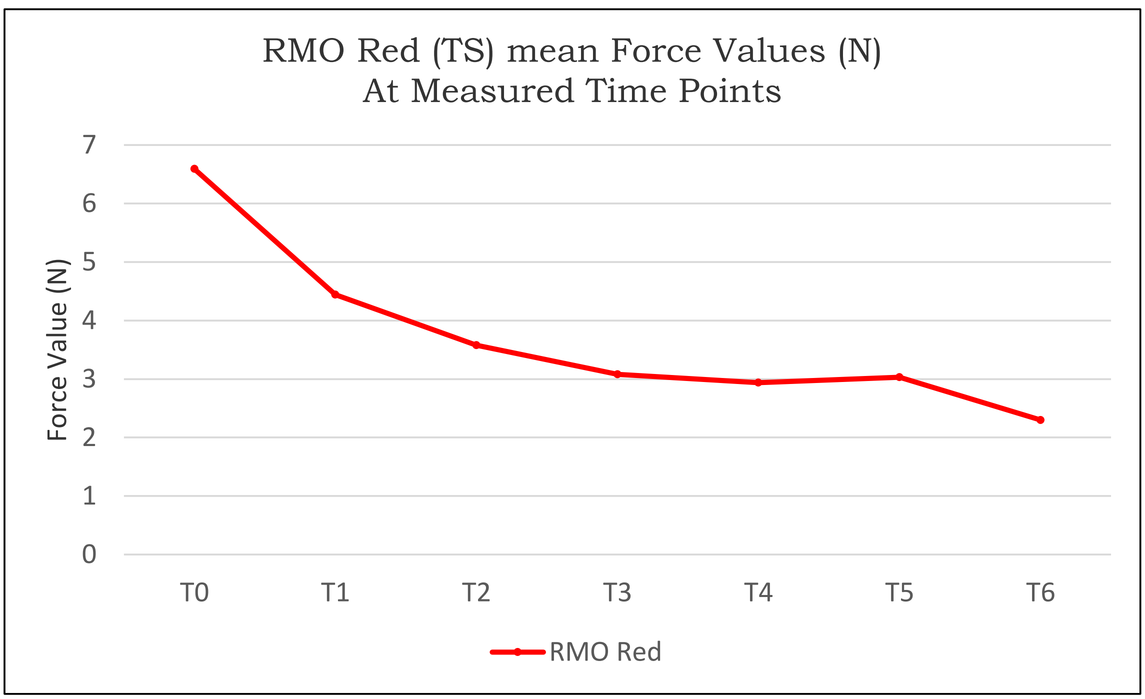
Ormco Generation II Grey (TS) Mean Force Values (N) at Measured Time Points
Force Value (N)
0
1
2
3
4
5
6
7
T0
T1
T2
T3
T4
T5
T6
ORMCO Memory Grey

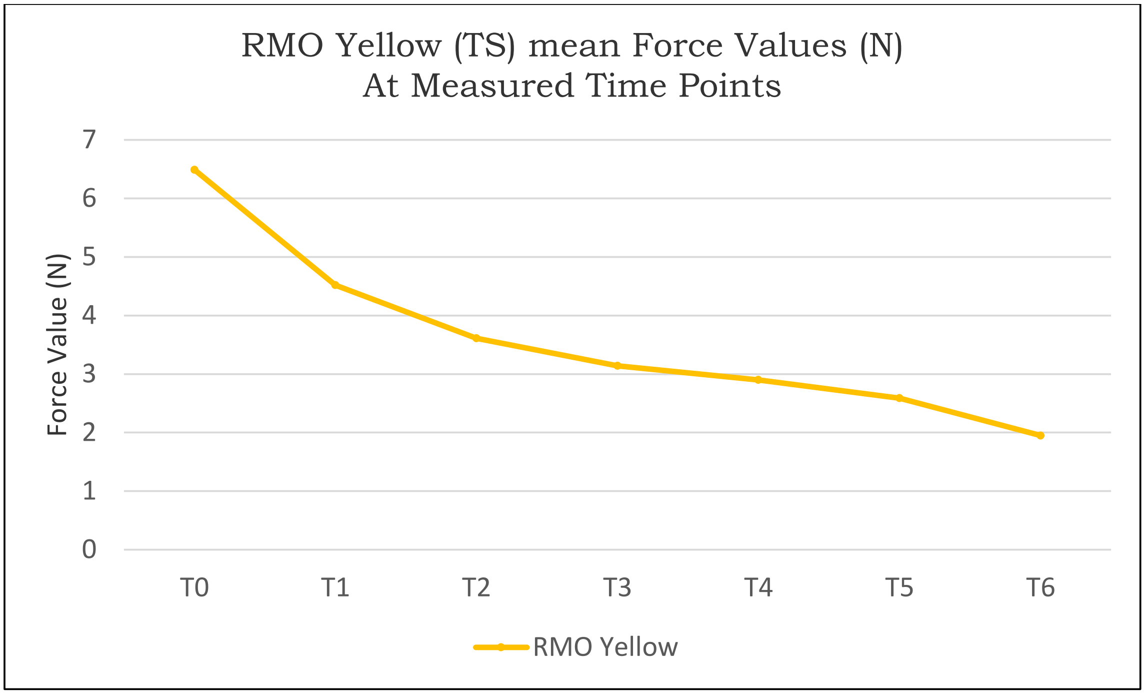


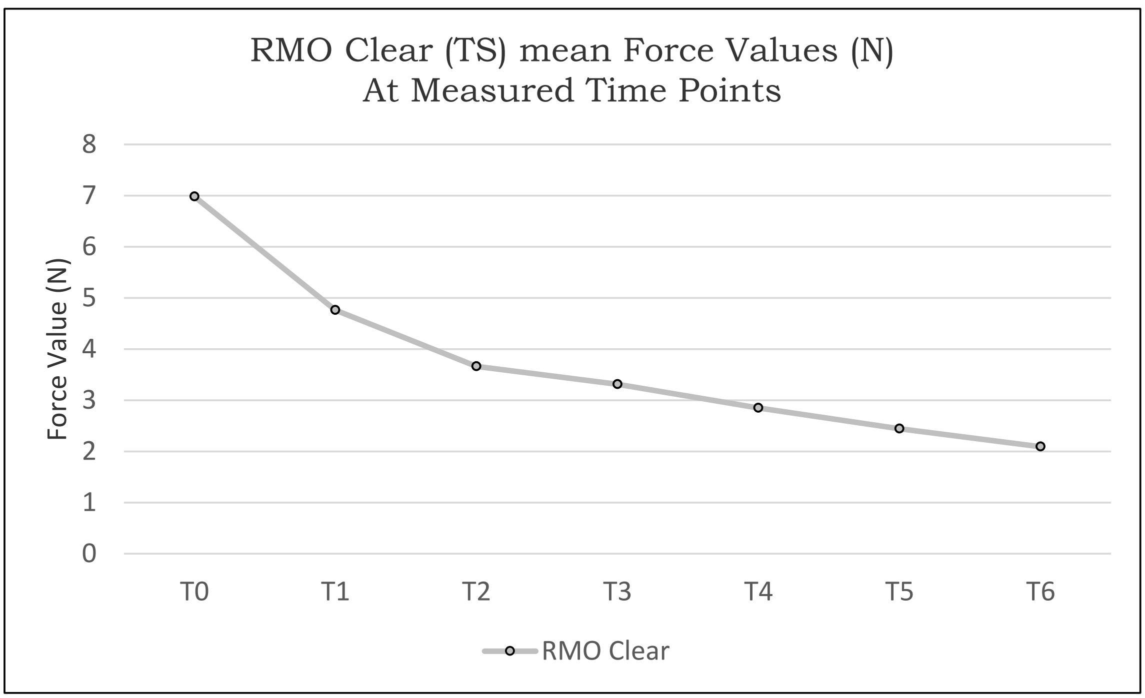
Ormco Generation II Clear (TS) Mean Force Values (N) at Measured Time Points
Force Value (N)
0
1
2
3
4
5
6
7
T0
T1
T2
T3
T4
T5
T6
Ormco Memory Grey

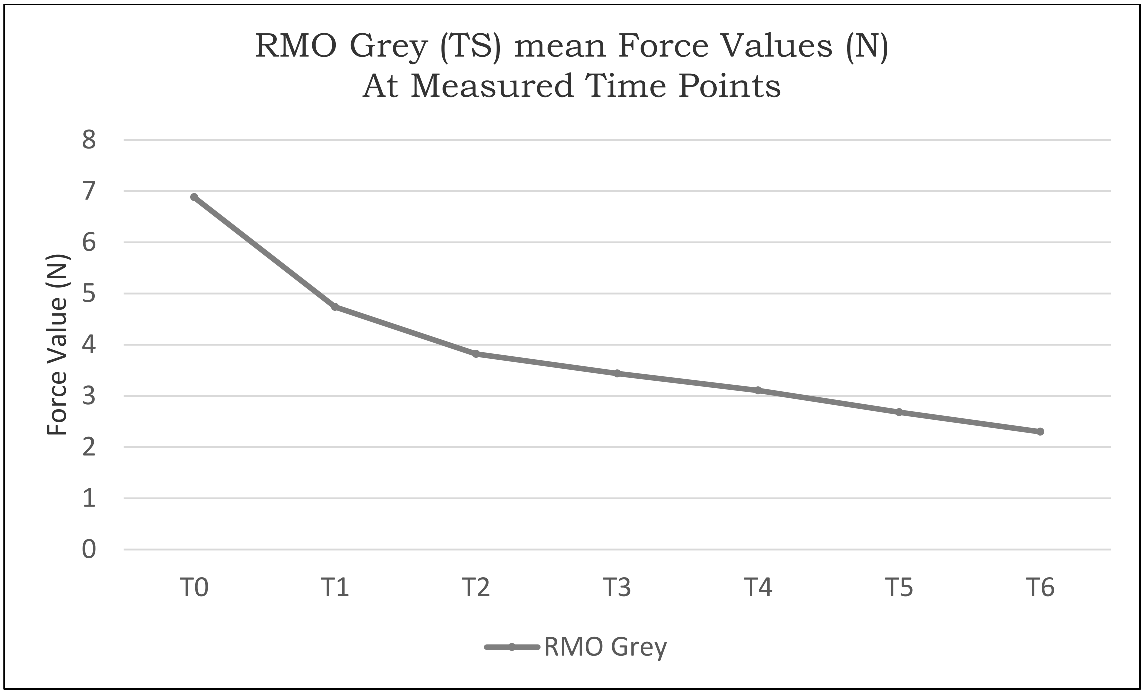
Appendix F: Force Displacement Behavior RMO



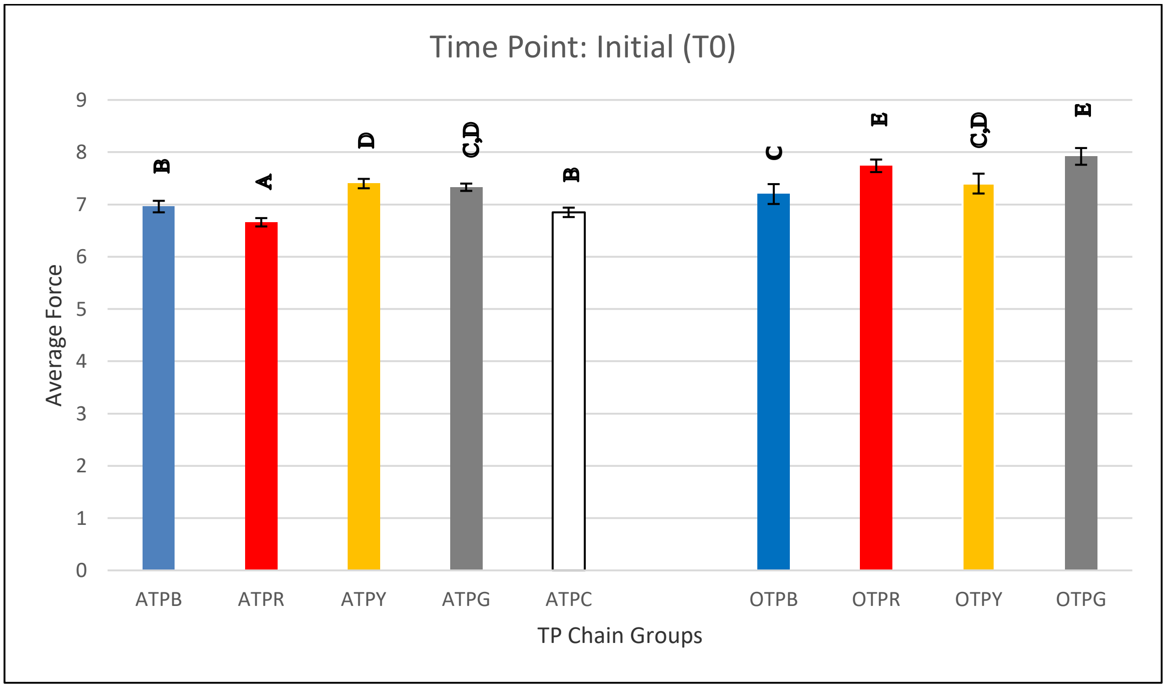



RMO Yellow (TS) mean Force Values (N)
At Measured Time Points
Force Value (N)
0
1
2
3
4
5
6
7
T0
T1
T2
T3
T4
T5
T6
RMO Yellow

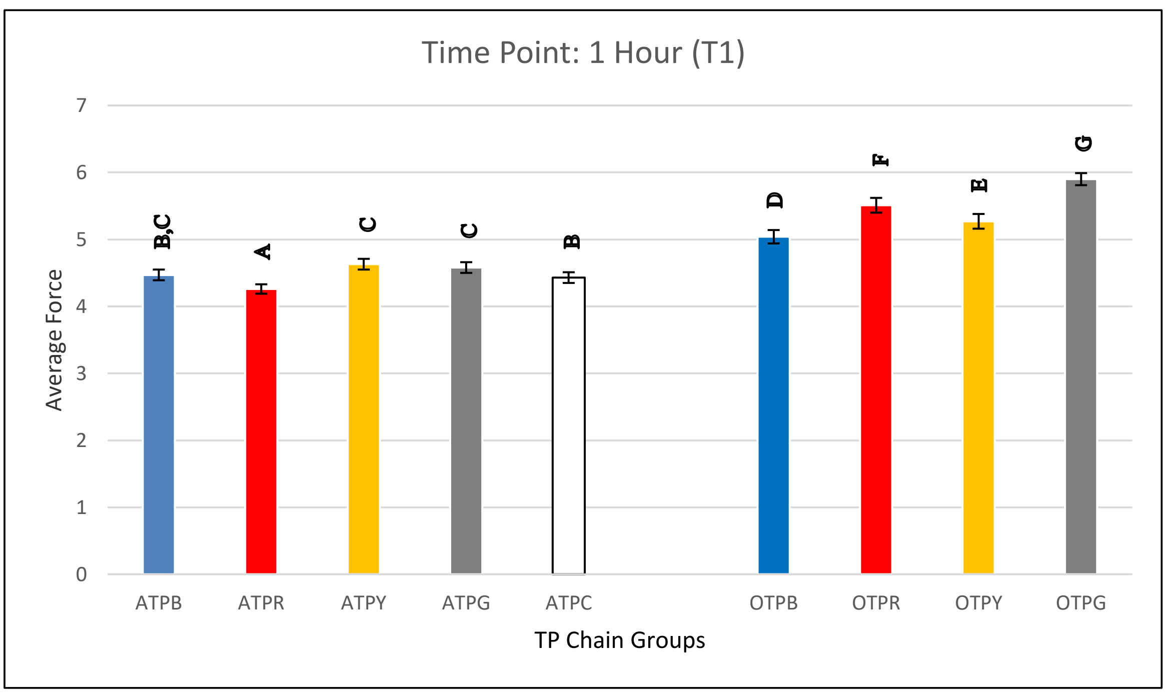

RMO Clear (TS) mean Force Values (N)
At Measured Time Points
Force Value (N)
0
1
2
3
4
5
6
7
8
T0
T1
T2
T3
T4
T5
T6
RMO Clear


RMO Grey (TS) mean Force Values (N)
At Measured Time Points
Force Value (N)
8
7
6
5
4
3
2
1
0
T0
T1
T2
T3
T4
T5
T6
RMO Grey

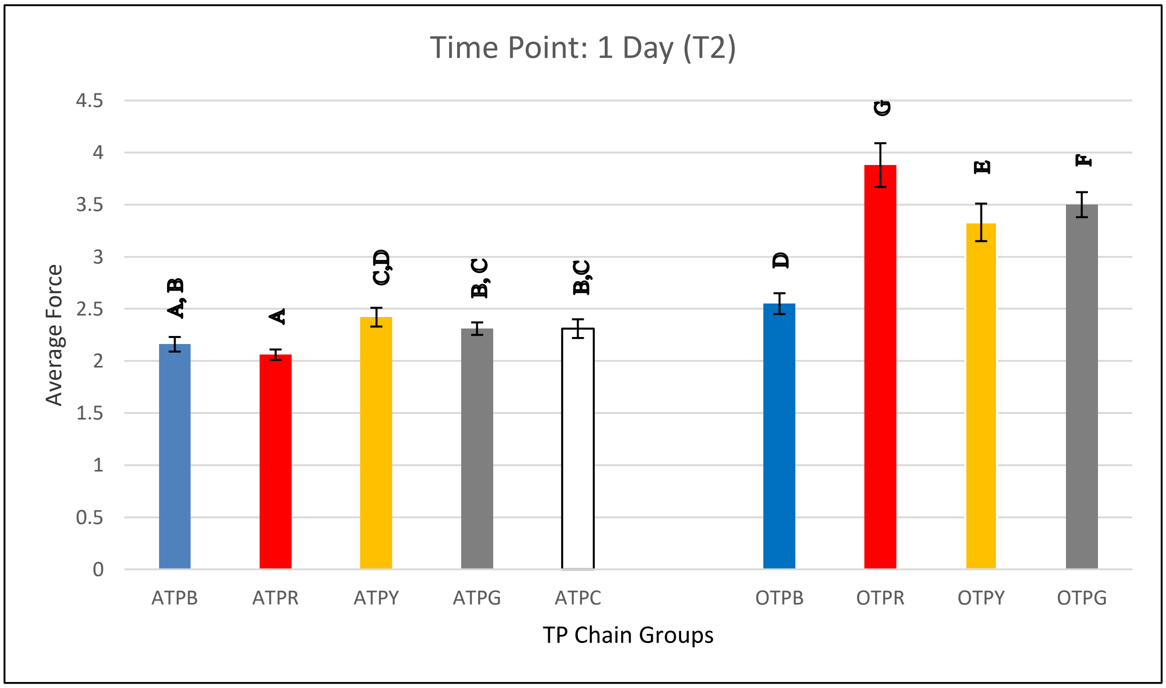
Appendix G. Mean Force Plots at Each Time Point for TP Chains



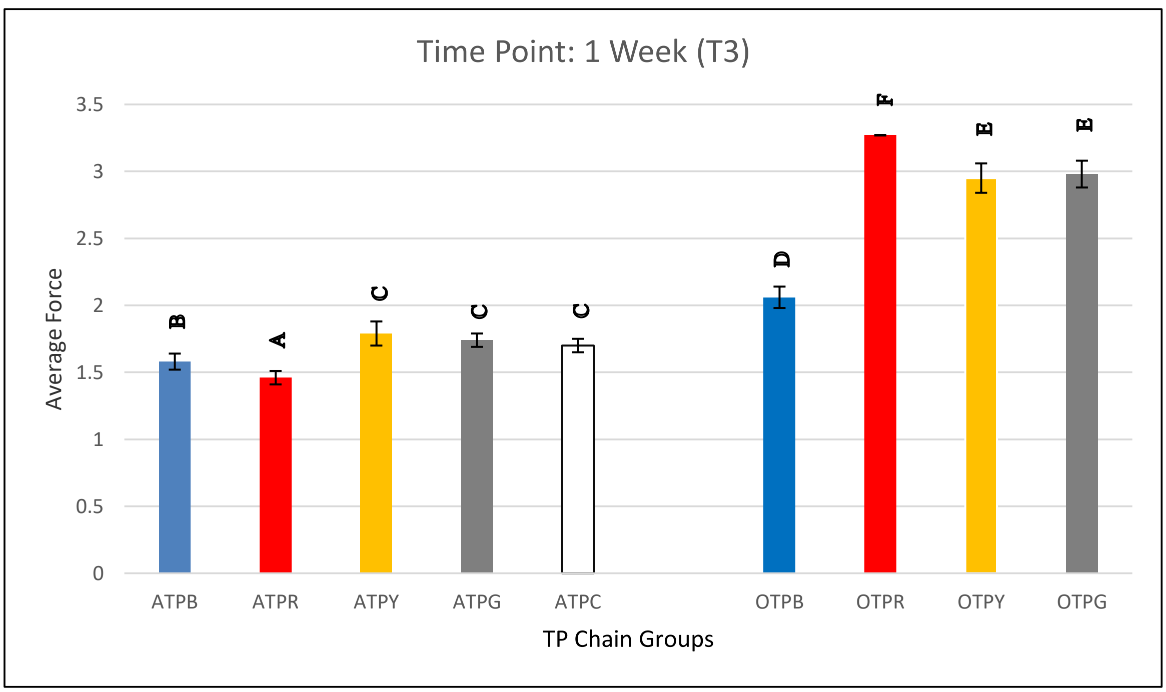
Different letters signify statistically significant differences between groups (p<0.05)



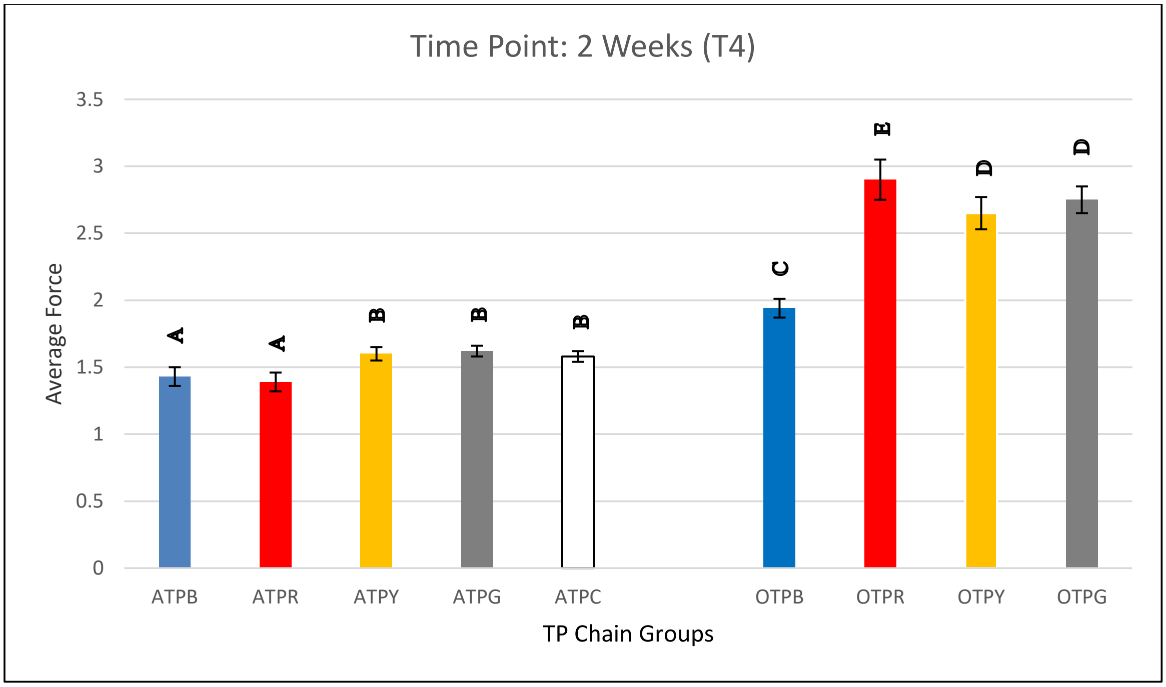
Different letters signify statistically significant differences between groups (p<0.05)



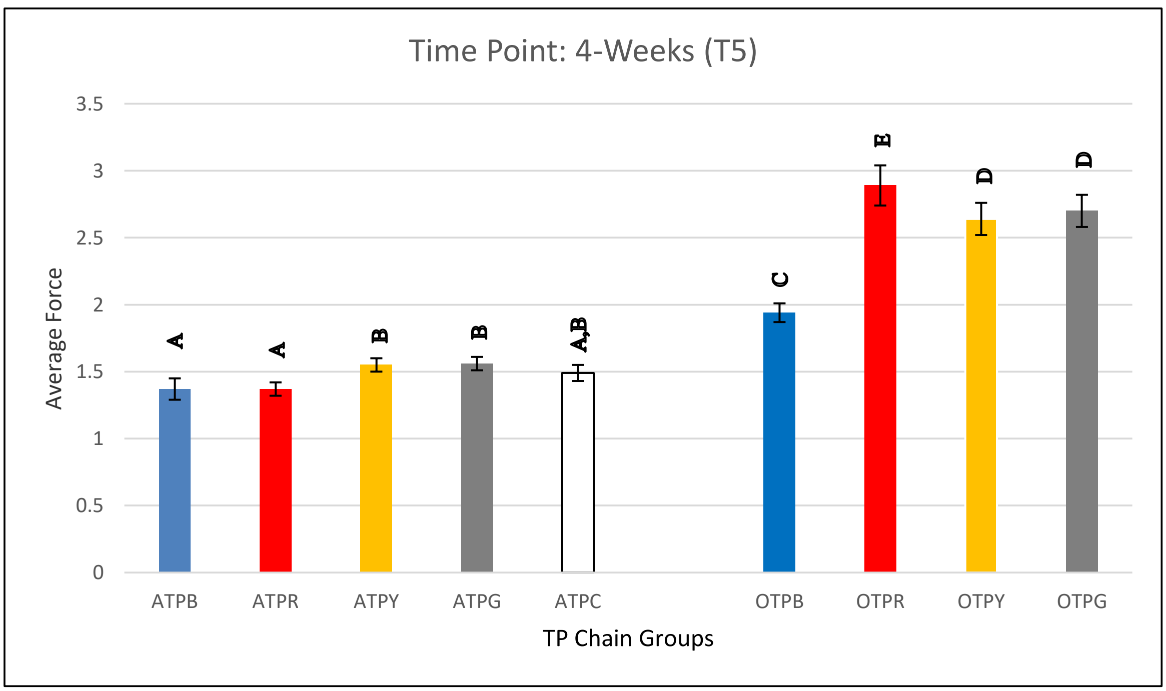
Different letters signify statistically significant differences between groups (p<0.05)



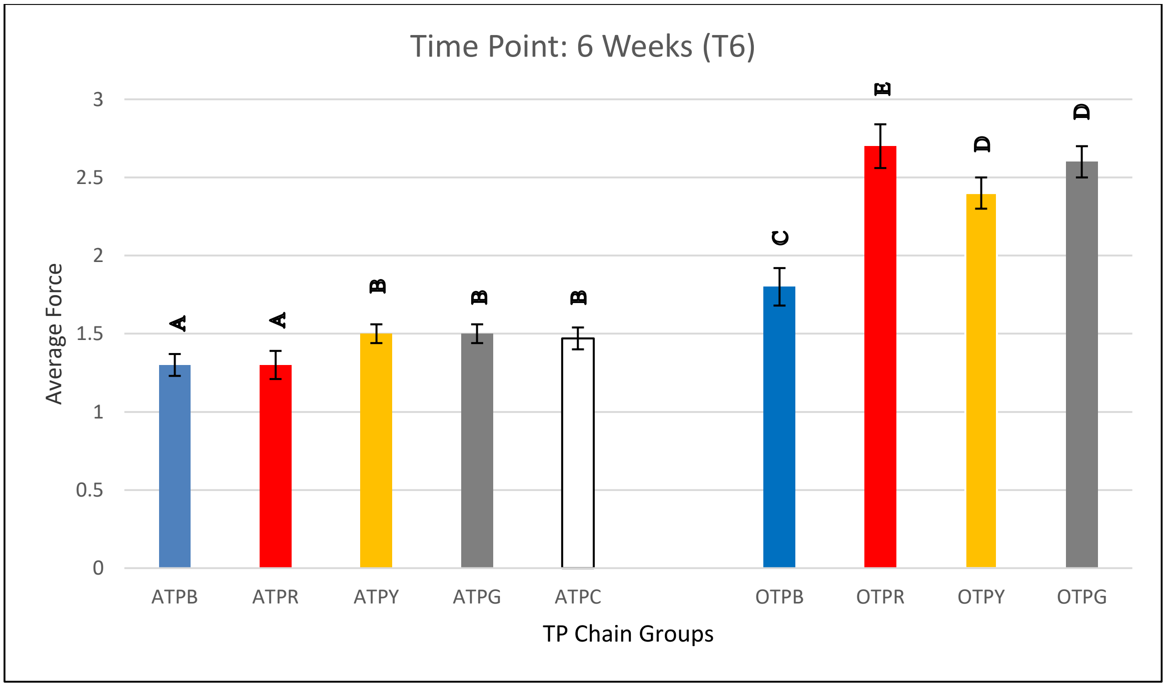
Different letters signify statistically significant differences between groups (p<0.05)



Different letters signify statistically significant differences between groups (p<0.05)

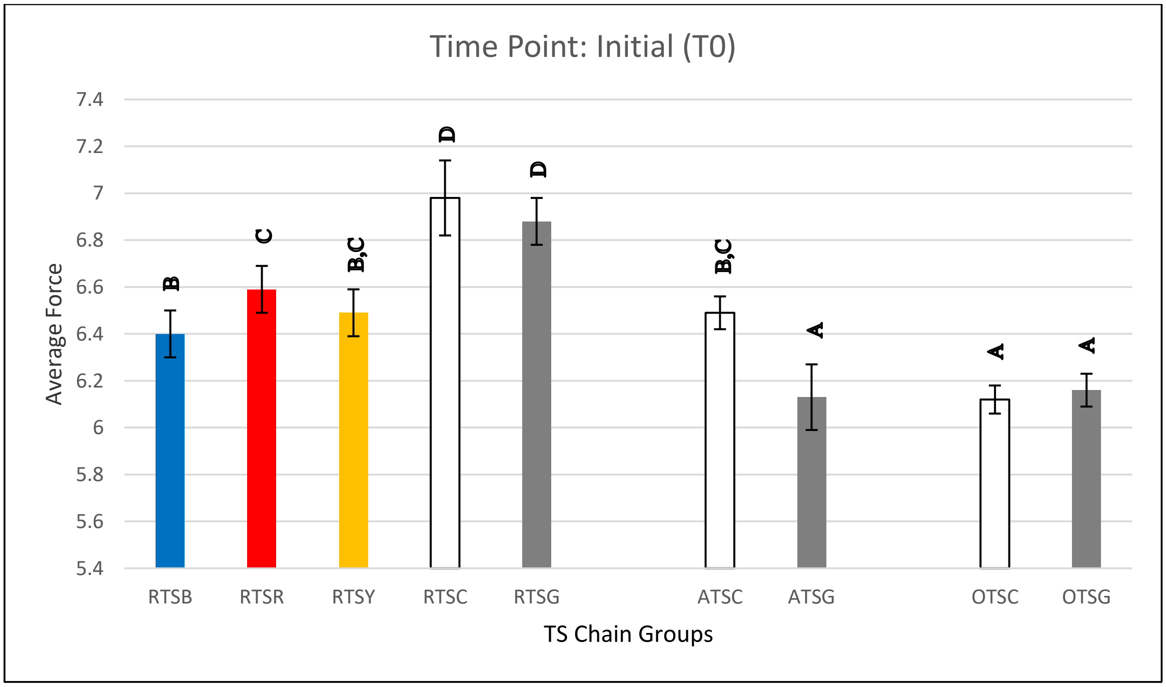


Different letters signify statistically significant differences between groups (p<0.05)

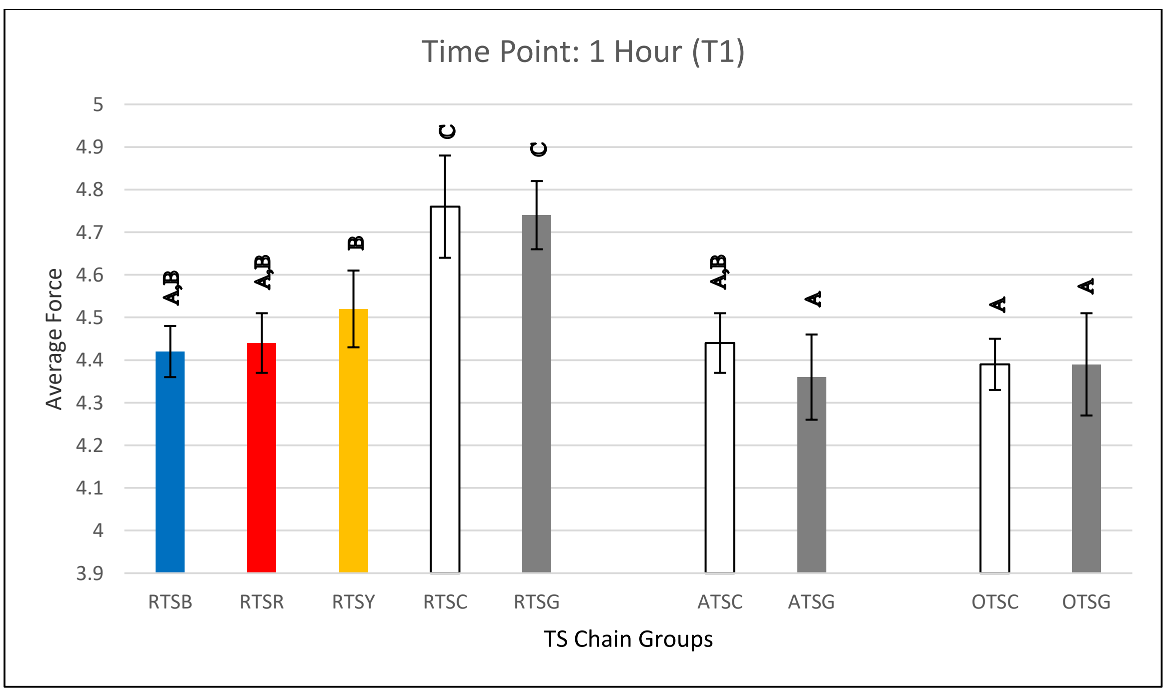


Different letters signify statistically significant differences between groups ($p<0.05$)

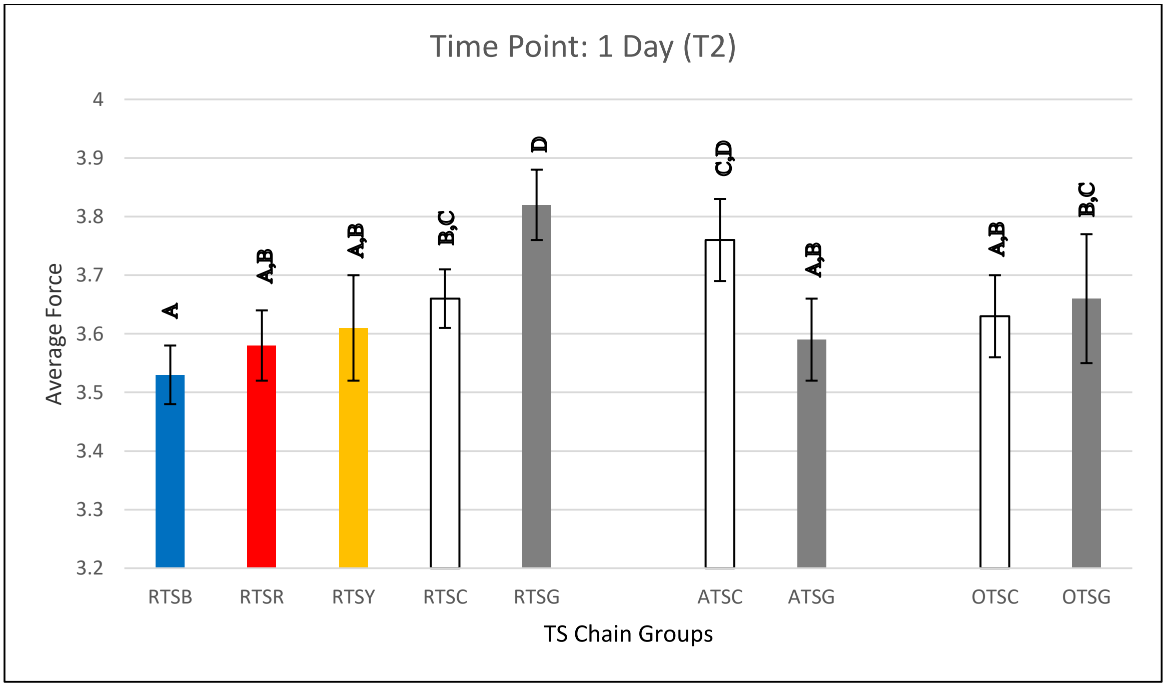
Appendix H: Mean Force Plots at Each Time Point for TS Chains



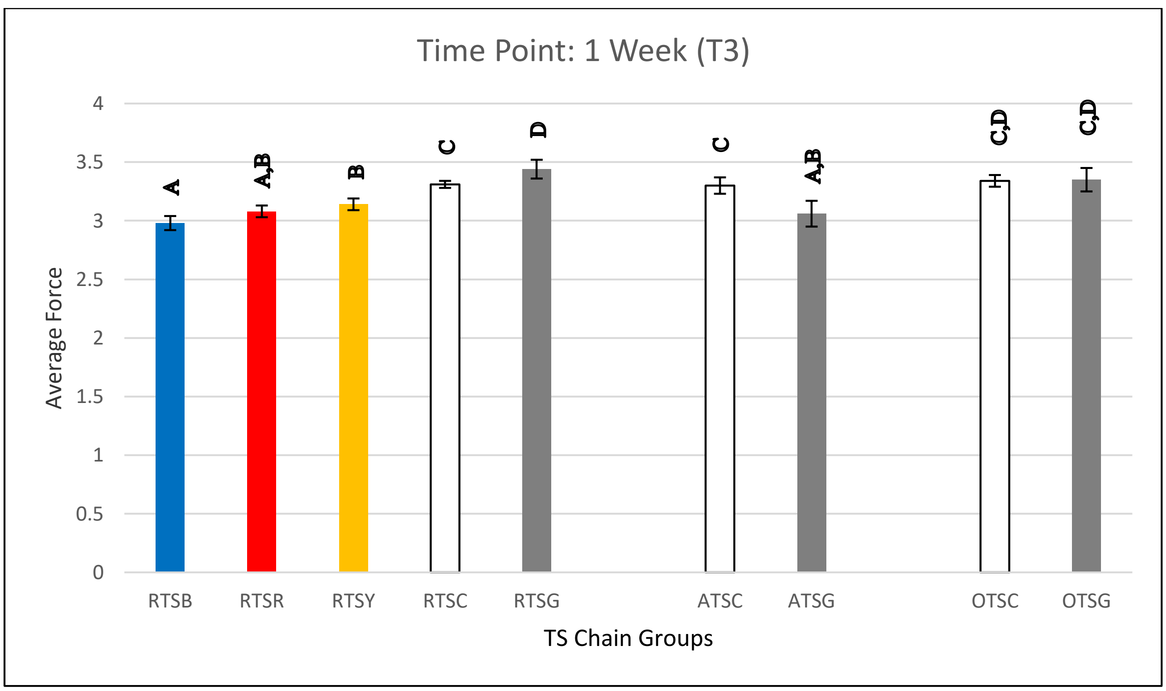
Different letters signify statistically significant differences between groups (p<0.05)



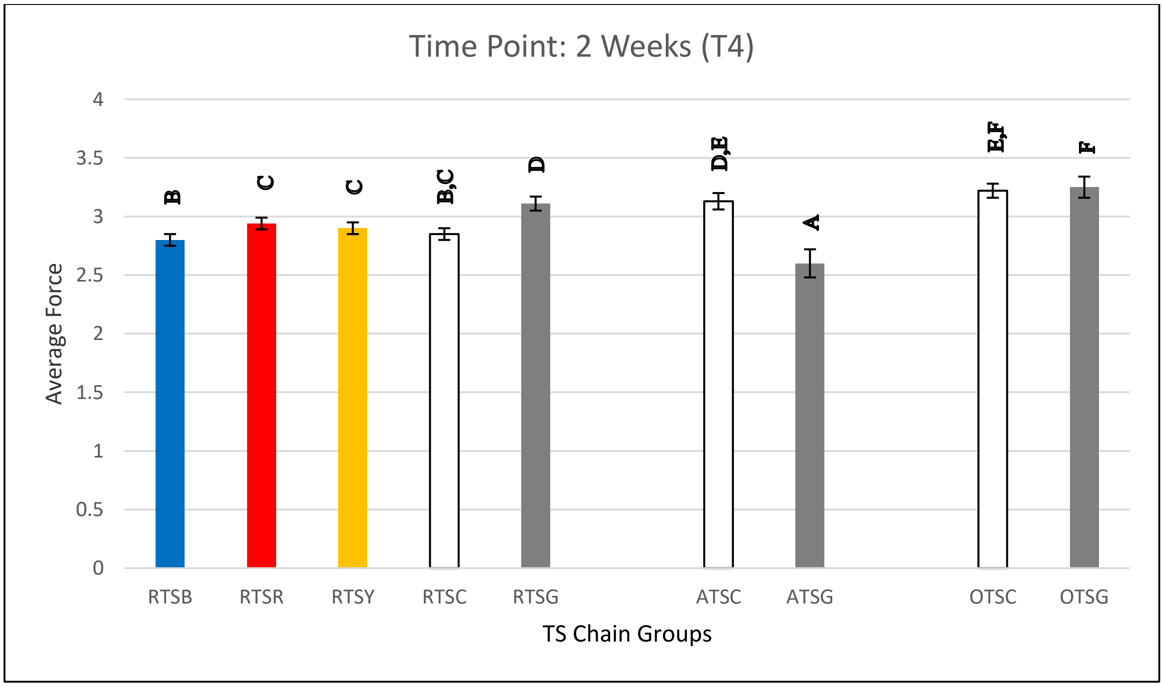
Different letters signify statistically significant differences between groups (p<0.05)



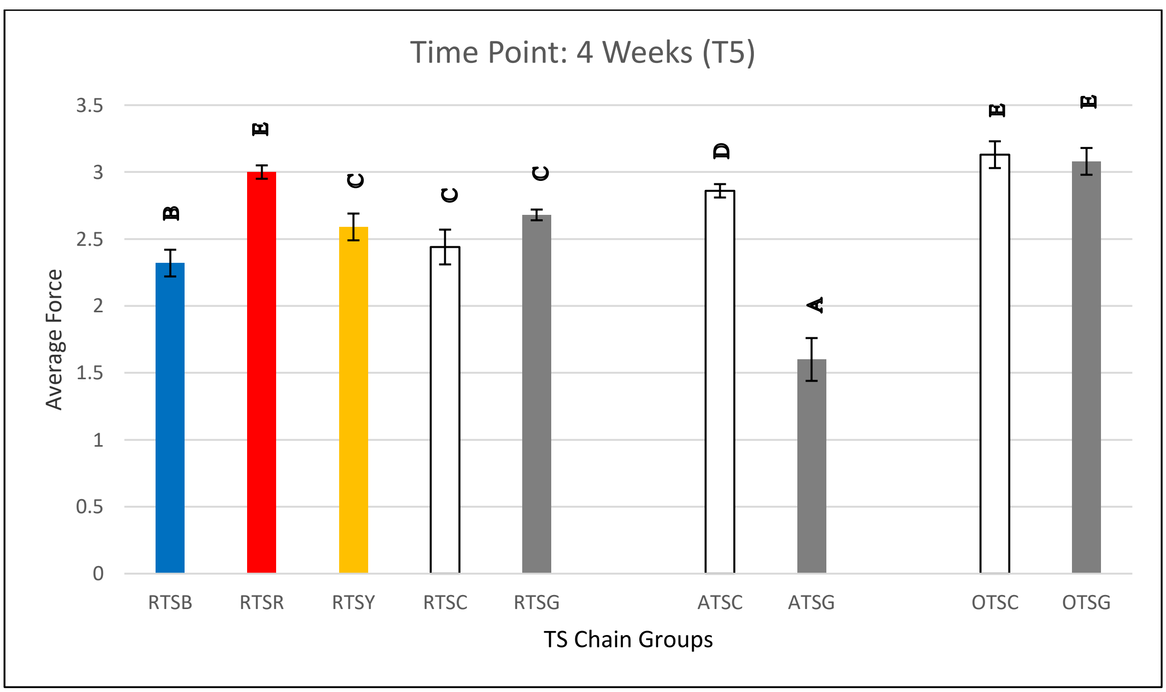
Different letters signify statistically significant differences between groups (p<0.05)



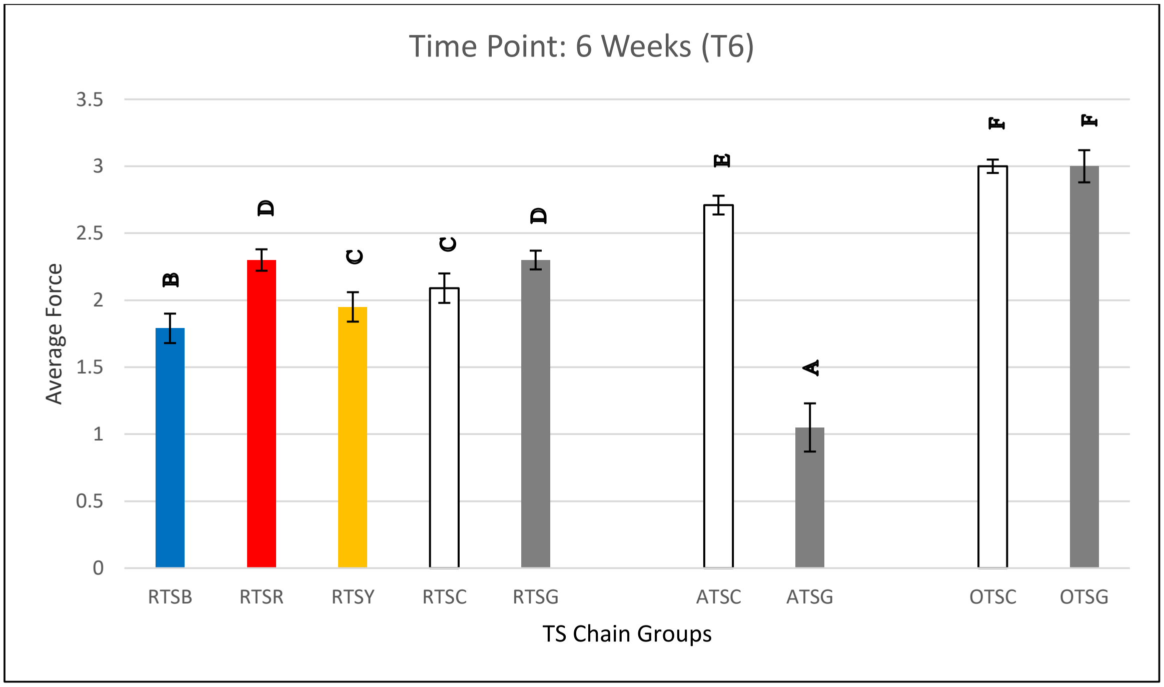
Different letters signify statistically significant differences between groups (p<0.05)



Different letters signify statistically significant differences between groups ($p<0.05$)



Different letters signify statistically significant differences between groups ($p<0.05$)



Different letters signify statistically significant differences between groups ($p<0.05$)

Curriculum Vitae

Name: William H.R. Taylor

Education:

2017-2020	Western University MCID Schulich School of Medicine & Dentistry – Graduate Orthodontics	London, ON
2002-2006	Dalhousie University DDS Faculty of Dentistry	Halifax, NS
1997-2002	Memorial University BSc. Department Chemistry and Mathematics	St John's, NL

Related Work Experience

2006-2017	Humber Valley Dental - General Dentist	Corner Brook, NL
2006-2009	Baie Verte Dental – General Dentist	Baie Verte, NL