DYNAMIC MECHANICAL ANALYSIS OF DIFFERENT BRANDS OF ORTHODONTIC ELASTOMERIC CHAINS

THESIS

Presented in Partial Fulfillment of the Requirements for

The Degree of Master of Science in the

Graduate School of The Ohio State University

By

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Graduate Program in Dentistry

The Ohio State University
2011

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ABSTRACT

Orthodontic elastomeric chains are commercially available from many manufacturers. **Objective:** This study investigated effects of manufacturing factors on dynamic force delivery and viscoelastic properties of elastomeric chains from three manufacturers using dynamic mechanical analysis (DMA). **Methods**: Three popular colors (clear, silver/gray, black) of elastomeric chains were obtained from three manufacturers (GAC, RMO, 3M Unitek). The dimensions for nine specimens of each colored brand (N=81) were measured, and DMA was performed at eight frequencies (0.125, 0.25, 0.5, 1.0, 2.0, 4.0, 8.0, and 16.0Hz). Five DMA variables [storage stiffness (K'), loss stiffness (K''), Tan δ, and damping (C)] were analyzed using repeated-measures ANOVA and pairwise t-tests, comparing all frequencies for each colored brand (Bonferroni correction) and all colored brands for each frequency (step-wise Bonferroni correction). Significance was set at α=0.05. **Results**: Significant differences were found among means of all four measured specimen dimensions. Comparing the five mean DMA variables for each colored brand, values for nearly all frequencies differed from one another. Comparing the mean DMA variables for each frequency, significant differences were also found for all variables and frequencies. **Conclusions**: Multiple manufacturing factors likely combine to affect dynamic force delivery and viscoelastic properties of elastomeric chains. Further research investigating clinical performance is recommended.

Dedicated to my mom and dad

ACKNOWLEDGEMENTS

I would like to thank my thesis committee, Dr. Brantley, Dr. Denry, Dr. Kim, Dr. Johnston, and Dr. Schricker for helping me construct and execute this study. Each of you has contributed tremendously to this project, and I know that without your patience, guidance, and brilliant minds, this project would not have been a success. I would like to also thank Dr. Claire Stroede for being a truly wonderful and incredibly generous colleague, co-researcher, and friend. This project would not have been half as enjoyable and seamless without her. I have gained a special friendship with you from this research.

To my parents, Afaf and Mohammed, I would like to first and foremost thank you both for the amazing love and support you have given me throughout the years. Thank you for encouraging me endlessly to pursue higher education and explaining to me how through education and knowledge comes enlightenment and humility. Both of you have inspired me to always do my best and to constantly challenge and better myself. As well, in my sad and difficult moments you were both endlessly comforting and even more supporting. You

have done your best to give me the opportunities and the means to pursue my dreams that were not available to either one of you growing up, and for that I am eternally grateful. I love you both very much and I dedicate everything to my loving parents. I am nothing without you and I am everything with you.

To my wonderful siblings, Rola and Atef, even though we have been far apart for a long time, I still feel the love and care every time we meet. I wish you both the very best in everything you pursue in life.

I would like to also thank all my faculty members at The Ohio State University for educating me and being great mentors. A special thanks goes to Dr. Ana Mercado for helping me see the true value in research and inspiring me to be a better researcher and clinician. Thank you so much for giving me an opportunity to work with you on the Americleft research and always encouraging me and helping me.

My fellow co-resident, Dr. Chan Chang, has my special gratitude for all the great memories together and for being a true friend to me. You have always been there when I needed you and for that I am forever grateful. You have been like a sister to me and will continue to be. Thank you for making this residency enjoyable.

To my best friend, Dr. Wissam Kamouni, I would like to thank you for always being there if I needed to vent or needed a warm smile

throughout the stressful times in my residency. You are a brother to me and it is an incredible blessing to have you in my life.

I would like to thank Dr. John D. Ryan for taking me under his wing and teaching me everything I know about dentistry. You have an enormously generous heart. I am always inspired by you and I thank you for standing by me and being my good friend.

Lastly, I would like to thank Delta Dental Master's Thesis Award Program for funding this research.

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CHAPTER 1

INTRODUCTION

Elastomeric chains are force-delivery appliances that are widely used in clinical orthodontics to close inter-dental spaces without concerns for patient compliance. These chains are available from many commercial sources in several configurations (continuous, short, and long), depending on the length of connector between the links. Past research has shown that the elastomeric chains are made from polyurethane, but minimal information is available about the proprietary fillers and pigments in the commercial products. They are processed by either die cutting or injection molding. Because many different brands and colors are available for currently marketed elastomeric chains, the orthodontist has a dilemma when trying to make a rational selection for clinical use. Thus, the objective of this study is to examine if different company methods of processing the polyurethane modules or chains can alter their viscoelastic properties.

COMPREHENSIVE LITERATURE REVIEW

AND

STATEMENT OF THE PROBLEM

The major clinical requirement for the elastomeric chains is the generation of appropriate *in vivo* forces. A large number of studies have focused on the force delivery and force decay of these appliances. Additional investigations have examined environtmental and manufacturing effects on the behavior of these chains. As well, the glass transition temperature (T_g) of these polyurethane appliances have been studied, since relative values of T_g are of importance in determining relative force delivery and force decay.

Force Decay and Prestretching

In 1994, Baty et al.[1] reviewed research on elastomeric chains.[2-14] In summary, they found that the elastomeric chains tend to lose 50%-70% of their initial force by the first day of activation. The chains also only retain 30%-40% of the original force after 3 weeks of activation. There seems to be a large variation in the initial force among the different manufacturers' chains. The recommendation to generate force levels biocompatible with tooth movement was to use a force gauge to determine the desired initial force.

In addition, Lu et al [15] compared the force decay of two types of power chains colors (clear, gray) from two different manufacturers (RMO, AO) submerged in water over the span of 6 weeks. The results of this study were in agreement with earlier studies where most of the force decay of all the chains occurred during the first hour after initial loading. As well, the greater the initial force the greater the force decay. It was found that RMO clear had the least amount of force decay compared to the rest of the chains. The authors' findings suggest that there are differences in the clinical behavior between different manufacturers as well as different colors of the same manufacturer.

Josell et al [16] conducted a force degradation comparison of open and closed gray power chains from six different power chain companies (TP, Ormco, RMO, GAC, AO, and Dentaurum). The chains were stretched to 28-mm constant stretch for 28 days in artificial saliva at room temperature. Again, their findings suggest all chains had force reduction over time with most of the force dissipation occurring in the first few days (especially the first hour) before reaching a plateau for the rest of the time. They noted that chains that delivered highest forces also had higher forces after degradation. TP

Closed chains and RMO closed and open chains had the highest percentage of initial force left. Also, they found significant differences between open and closed chains of the same manufacturer, which suggests that dimension might play a role in force degradation. They concluded that knowing the percentage of initial force that a particular company's power chain can maintain helps the clinician determine what initial stretching and force levels to apply for tooth movement.

More recently, an in-vitro study of force decay of power chains was done to compare it to NiTi coil spring force decay.[17] The study compared four manufacturers (Morelli, Abzil, TP, American) power chains with the same manufacturers' NiTi coil spring. They did find differences in the initial force delivered by the different manufacturers and the force decay was more than NiTi coils. Their study supported the notion that brand effects exist in the force delivery properties of elastomeric chains.

To improve the force delivery of power chains and somewhat decrease the rapid force decay rate, prestretching of the elastomeric power chains had been suggested. However most previous studies have shown that although there was a statistical significant reduction in force decay (around 5%), clinically significant impact is questionable to the large force decay on average of power chains (50%-70%).[18]

More recent research by Kim et al[18] looked at prestretching on time-dependent force decay of power chains showed similar findings. The chains were placed in distilled water and stretched 100% of their length and the forces were measured at 1 hour, 24 hours, and then weekly for four weeks. They discovered significant force decay in all samples (especially in the first 24 hours) and similar forces were found between prestretched and the control groups after 4 weeks. Hence, they concluded that prestretching did not seem to offer any clinical value over non-stretching.

Factors affecting physical properties of elastomeric chains

Generally elastomeric chains share a common theme of force decay and mechanical properties as described above, however, there seems to be significant variations under different environmental conditions and among different elastomeric products.[1]

Earlier studies have looked at environmental factors effects on elastomeric chains such as tooth movement, temperature changes, PH variations, oral fluoride rinses, salivary enzymes, and masticatory forces.[1, 9, 19, 20] These factors seem to have an effect on the deformation, force degradation, and relaxation behavior of the elastomeric chains. It was concluded that when exposed to the oral environment, the elastomeric chains absorb water and saliva, permanently stain, and suffer breakdown of internal bonds leading to permanent deformation. It was also suggested that these chains be kept in the manufacturer's container and protected from direct light.

In 1994, research by Stevenson and Kusy[21] looked at the degradation effects on three elastomeric chains that were treated in solutions of varying acidity, oxygen content and temperature. Of all the variables they looked at, they concluded that temperature had the greatest role in chain degradation.

Eliades et al[22-24] looked at the structural characteristics, tensile strength, permanent elongation, and toughness of elastomeric chains. They looked at open and closed products of three unspecified brands of elastomeric chains. The chains were studied in the as-received state, after 24 hours in air, after 24 hours of intraoral exposure, and after three weeks of intraoral exposure. They found the in vivo specimens developed a proteinaceous biofilm within 24 hours, which calcified in three weeks. Due to this biofilm, it was mentioned that the intraoral placement of these chains can be seen as an impediment to the force delivery and behavioral properties of the elastomeric chains. They also found no significant effects on elongation based on module geometry or design, nor was there an observed correlation between specimen treatment and tensile strength. These "terminal" properties of the material, such as tensile strength, seem not to be sensitive to environmental changes. These finding seems contradictory to previous research that shows that alteration in environmental variables substantially modifies the force decay of elatomers[9, 10]. The authors mentioned that due to the relatively reduced force magnitude developed during stretching in orthodontics and the unique intraoral environment as opposed to the implantable devices used in the studies might explain this discrepancy.

In 2008, Telxeira et al evaluated in vitro the effect of light Coke, phosphoric acid, and citric acid on the force decay pattern of two different gray elastomeric chain types (Sunburst,Chainette) manufactured by the same company (GAC). They found that immersion environment did not seem to alter the force decay of both chain types. The elastomers showed similar force decay as other studies. However, the Chainette chains had less force decay than the Sunburst. These results are in disagreement with previous studies done that showed significant changes in the mechanical properties of the elastomeric chains immersed in different environments[19, 25]. The authors attributed the differences in the fact that their specimens were not immersed continuously in the acidic solutions but only partially as would be in the oral cavity.

The effects of fluoride mouth rinses on the elastomeric chains have been studies previously by Von Fraunhofer et al.[26] They showed that only 31% APF had any effect on the force delivery and decay rate of elastomeric chains. More recently, Ramazanzadeh et al[27] showed that daily use of NaF did not affect force degradation for conventional orthodontic forces, but for higher forces there was an increase in force decay under fluoridated conditions.

Manufacturing Differences

Significant variations between different elastomeric chains have been noticed in past studies with regards to physical properties.[1] These differences can be attributed to processing variations in manufacturing techniques, additives or coloring fillers incorporated in the final product, and/or different dimensional characteristics of the chains.

Previous studies have indicated that even the configuration of the chain (open or closed) can affect the behavior of these elastomeric chains.[9, 28] Generally, it seems that the closed elastomeric chain exhibits a greater initial force and less force decay than the open type.[1]

An in vivo comparison of force decay between gray die-cut stamped and injection molded of the same manufacturer's elastomeric chains was done in 2006.[29] They found no statistically significant differences in the magnitude of the forces delivered or decayed produced by the same company's (AO) two manufacturing methods of power chains. This study might suggest that the method of production does not have an important role in the clinical behavior of elastomeric power chains.

Baty et al[14] tested force delivery properties in colored elastomeric chains. They looked at three manufacturers (Masel, Ormco, and Unitek) comparing five different colors (gray, pink, blue, green, and purple) for Ormco. The results indicated force delivery behavior of chains varies with the manufacturer and that Ormco purple and green chains required greater extension to provide physiologic forces. They concluded that color had some affect on the clinical force-extension behavior of the elastomeric chains.

Another recent study by Dittmer et al[30] looked at tensile properties of orthodontic elastomeric chains from eight different manufacturers (open and closed). They recorded the forces produced by the samples during different stretching lengths. The samples were extended to four times their initial length, reduced to three times the length, and finally stretched again to failure. They observed a pronounced hysteresis on all chains that produced higher forces on the very initial stretching which could lead to excessive forces clinically if the chains are not prestretched. Their results also showed that different elastomeric chains had different tensile properties, which means that the orthodontic forces produced by these chains depend on the type of elastomeric chain.

Glass Transition Temperature

Research at The Ohio State University using DSC analysis to investigate the glass transition temperature of elastomeric power chains was conducted to indirectly characterize the structural and behavioral effects of different manufacturers and pigmentation on these chains.[31, 32] In 2004, Renick et al, tested three colors (gray, red, purple) of elastomeric chains from three companies (RMO, Ormco, and G&H). They found that RMO had a significantly higher glass transition temperature than Ormco and G&H chains, which suggests that RMO chains might be less flexible than the other two brands. They also found that the purple G&H chains had lower glass transition temperature than the gray or red, which suggests that pigmentation of the elastomeric chains might change the mechanical properties of the chains within the same brand.

As a master's thesis, Casaus et al[31] also looked at glass transition temperature for six different colors (black, gray,clear, smoke, pearl, and silver) from the same manufacturer (GAC). They found that pigmentation significantly decreases the glass transition temperatures of the colored elastomeric chains when compared to the clear chains. However, they did mention that it might not be clinically significant and further research need to be undertaken.

DMA

Dynamic mechanical analysis (DMA) is used to examine the viscoelastic nature of polymers. It can test any material exhibiting viscoelastic behavior. To date, no research has been conducted on elastomeric chains using DMA.

Statement of the Problem

Previous studies have shown that different brands of elastomeric chains can have different force delivery, force decay, and glass transition temperatures. However, no studies to date have used Dynamic Mechanical Analysis (DMA) testing to evaluate dynamic force delivery and viscoelastic properties of elastomeric chains.

Specific Aims and Hypotheses

The objective of this research is to compare force delivery and viscoelastic properties of different brands of colored elastomeric chains using load-displacement and DMA testing. The specific aim is to evaluate the effects of manufacturing factors on dynamic stiffness, storage stiffness, loss stiffness, tangent of phase angle, and damping of elastomeric chains.

Null Hypotheses

1. Different brands of elastomeric chains will not have significantly different dynamic stiffnesses.
2. Different brands of elastomeric chains will not have significantly different storage stiffnesses.
3. Different brands of elastomeric chains will not have significantly different loss stiffnesses.
4. Different brands of elastomeric chains will not have significantly different tangents of phase angle.
5. Different brands of elastomeric chains will not have different dampings.

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after orthodontic use. Am J Orthod Dentofacial Orthop. 2004 Sep;126(3):337-43.

CHAPTER 2

MATERIALS AND METHODS

Power Chains

Three popular colors (black, silver/gray, and clear) of elastomeric chains were donated from three different manufacturers (one spool of each colored brand):

1. GAC International Inc (Bohemia, NY), Sunburst^{TM} Chains (black, silver, clear)
2. 3M Unitek (Monrovia, CA), Bobbin Alastik^{TM} Chains (black, gray, clear)
3. RMO (Denver, CO), Energy^{TM} Chain (black, gray, clear)

All power chains samples were non-expired, visually defect free, closed link, and die-cut that came in spool form. The power chain specimens to be tested were a total of seven links. Three center links between the machine text fixtures, two links on test fixtures, and two links to aid in installing on test fixtures.

Three four? dimensions of power chain specimens were measured:

1. Thickness at each of the 3 center links
2. Distance between the outer edges of the 5 center holes
3. Outside diameter of each of the center link
4. Inside diameter of the center link

All measurements were done by one person (H.S.). Each measurement was performed three times using a generic caliper accurate to 0.02 mm. Two blocks of specimens were re-measured for reliability within one week. Intra-class correlations (ICC's) and their 95% confidence intervals (CI) were calculated for each of the four measured dimensions.[1] ICC's were found to be above 0.95 for all dimensions. The operator's measurement reliability was found to be good for all four dimensions.

A sample size of nine was needed after a pilot study was conducted to determine sample size that allows 0.1N/mm detection difference in K* at power=0.92 and α=0.05. The power analysis was performed using the G*Power program (version 3.1 for Windows, Institute of Experimental Psychology, Heinrich Heine University, Düsseldorf, Germany).[2] Nine specimens were grouped into nine blocks (N=81). One specimen of each colored brand in each block. The test sequence within each black block was randomized. All specimens of all blocks were tested the same day. The testing was done at room temperature in laboratory air. This was not expected to dramatically affect elastomeric chains versus mouth temperature since their glass transition temperature are significantly lower than room temperature. [3,4]

DMA Testing Apparatus

DMA analysis of the specimens was performed using Bose ElectroForce® testing machine (Bose Corporation, ElectroForce Systems Group, Eden Prairie, MN). The machine has a load cell of up to 450N with a range of +/- 5mm. Custom fixtures were used to enable attachment of power chains to machine. Control of the machine is provided by the Bose WinTest® software (version 4.0, Bose Corporation, ElectroForce Systems Group, Eden Prairie, MN), digital control system.

DMA Testing Protocol

To obtain a more reproducible DMA testing, the specimens need to be tested within the elastic load-displacement range.[5] Figure 1 shows the nine colored brand specimens load-displacement plots. The plots show a linear behavior of these chains above 2 mm. Kovatch et al,[6] showed that the rubbery elastic behavior of a polymer occurs until the load-displacement curve encounters a change in slope named an inflection point. Hence, DMA testing for our specimens should be performed above 2 mm. The specimens were attached to the fixtures and slightly stretched to a "just taut" condition (<0.8N). Zero position defined as 34mm between 2 flat areas on test fixtures measured with a ruler, and care taken not to rotate the fixtures with respect to one another. This position allowed every specimen to be taut but not overly stretched (<0.8N). Every test specimen has a common starting length, but a different starting load. We observed that the power chains from each color and manufacturer exhibit cyclical softening. We cyclically softened the specimens in a controlled manner immediately before performing the DMA tests. The cyclical test consists of 20 cycles tested at 1 Hz in displacement control between 0.5 and 4.0 mm. DMA test will be performed immediately after the cyclic softening test, without removing the specimen from the test fixtures. Each DMA test will be run between 3.0 and 4.0 mm (based on visual inspection of load vs. displacement plots) at the following 8 frequencies: 0.125, 0.25, 0.5, 1.0, 2.0, 4.0, 8.0, and 16.0 Hz. The following data will be obtained for each DMA test: raw load vs. displacement data at each frequency, and DMA summary data. The DMA summary data of interest includes K* (dynamic stiffness), K' (Storage Stiffness), K'' (Loss Stiffness), Tangent δ, and damping.

Statistical Analysis

Statistical analyses were performed using SAS software (version 9.2, SAS, Cary, NC). ANOVA and Ryan-Einot-Gabriel-Welsch multiple range tests was used to analyze the four dimensional variables. Repeated-measures ANOVA and pairwise t-tests were used to on the five DMA variables (K*, K′, K′′, Tan δ, and damping). Frequency was considered the repeated factor since each specimen was tested at eight different frequencies. Pairwise t-tests compared all frequencies for each colored brand, and a standard Bonferroni correction was applied. Pairwise t-tests also compared all colored brands for each frequency, and a stepwise Bonferroni correction was applied.

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CHAPTER 3

MANUSCRIPT

DYNAMIC MECHANICAL ANALYSIS OF DIFFERENT BRANDS OF ORTHODONTIC ELASTOMERIC CHAINS

ABSTRACT

Orthodontic elastomeric chains are commercially available from many manufacturers. **Objective:** This study investigated effects of manufacturing factors on dynamic force delivery and viscoelastic properties of elastomeric chains from three manufacturers using dynamic mechanical analysis (DMA). **Methods**: Three popular colors (clear, silver/gray, black) of elastomeric chains were obtained from three manufacturers (GAC, RMO, 3M Unitek). The dimensions for nine specimens of each colored brand (N=81) were measured, and DMA was performed at eight frequencies (0.125, 0.25, 0.5, 1.0, 2.0, 4.0, 8.0, and 16.0Hz). Five DMA variables [storage stiffness (K'), loss stiffness (K''), Tan δ, and damping (C)] were analyzed using repeated-measures ANOVA and pairwise t-tests, comparing all frequencies for each colored brand (Bonferroni correction) and all colored brands for each frequency (step-wise Bonferroni correction). Significance was set at α=0.05. **Results**: Significant differences were found among means of all four measured specimen dimensions. Comparing the five mean DMA variables for each colored brand, values for nearly all frequencies differed from one another. Comparing the mean DMA variables for each frequency, significant differences were also found for all variables and frequencies. **Conclusions**: Multiple manufacturing factors likely combine to affect dynamic force delivery and viscoelastic properties of elastomeric chains. Further research investigating clinical performance is recommended.

INTRODUCTION

Elastomeric chains are force-delivery appliances that are widely used in clinical orthodontics to close interdental spaces without concerns for patient compliance. These chains are available from many commercial sources in several configurations (continuous, short, and long), depending on the length of connector between the links. Past research has shown that the elastomeric chains are made from polyurethane, but minimal information is available about the proprietary fillers and pigments in the commercial products. They are processed by either die cutting or injection molding. Because many different brands and colors are available for currently marketed elastomeric chains, the orthodontist has a dilemma when trying to make a rational selection for clinical use.

Since the major clinical requirement for the elastomeric chains is the generation of appropriate in vivo forces, a large number of studies have focused on the force delivery and force decay of these appliances.[1-32] Additional investigations have examined the glass transition temperature (T_g) of these polyurethane appliances, since relative values of T_g are of importance in determining relative force delivery and force decay.[32-36] Baty et al[37] reviewed research prior to 1990, summarizing that the elastomeric chains lose 50-70% of initial force during the first day of activation and only retain 30-40% after 3 weeks. More recent articles reported that the force decay over a one-month period ranges from 22%-72%.[23,28] There have been numerous articles showing that this force degradation might depend on the manufacturing factors.[19,21,23,28-32]

This research looks at dynamic mechanical analysis (DMA) of colored elastomeric chains, focusing on comparisons between three manufacturers for three products of the same color. DMA is commonly used to examine the viscoelastic nature of polymers. However, there have been no previously published articles on the use of DMA to evaluate the dynamic force delivery and viscoelastic properties of elastomeric chains.

MATERIAL AND METHODS

Three popular colors (black, silver/gray, and clear) of elastomeric chains were donated by three different manufacturers (one spool of each brand and color): (1) GAC International Inc (Bohemia, NY), Sunburst™ (black, silver, and clear), (2) 3M Unitek (Monrovia, CA), Bobbin Alastik™ (black, gray, and clear), (3) RMO (Denver, CO), Energy™ (black, gray, and clear). All elastomeric chain spools provided were non-expired, visually free of defects, closed-link, and die-cut, and individual five-link specimens were utilized.

The length, thickness, inside diameter, and outside diameter of all test specimens were measured by one operator (H.S.) prior to testing using a digital caliper accurate to 0.02 mm. The three middle links were each measured three times, and average values were calculated. To test measurement reliability, a set of 18 untested specimens (two of each color from each brand) was measured two times by the same operator (H.S.) one week apart. Intra-class correlations and their 95% confidence intervals (CI) were calculated for each of the four measured dimensions.[38]

DMA analysis of the specimens was performed using Bose ElectroForce® testing machine (Bose Corporation, ElectroForce Systems Group, Eden Prairie, MN). The machine has a load cell of up to 450N with a range of +/- 5mm. Custom fixtures were used to enable attachment of power chains to machine. Control of the machine is provided by the Bose WinTest® software (version 4.0, Bose Corporation, ElectroForce Systems Group, Eden Prairie, MN), digital control system.

The load-displacement behavior of all specimen types was investigated by DMA between 0 mm and 4.5 mm of displacement. All specimens were tested within the elastic range, using the criterion originally reported for the rubber elasticity behavior of the polyurethane modules by Kovatch et al.[5] Because the test specimens had a non-standard geometry, all measurements were performed in terms of displacement and load based on the given specimen geometry. The DMA parameters calculated were: (1) K*, the dynamic stiffness, (2) K′, the elastic component of K*, termed storage stiffness, (3) K′′, the viscous component of K*, termed loss stiffness, and (4) Tan δ (Tangent δ) = K′′ / K′, where δ (termed the phase angle) is the angle between applied displacement and measured load (5) Damping.

A preliminary (pilot) study showed that a sample size of N=9 specimens of each color/brand combination was required to detect a 0.1 N/mm difference in K* at power=0.92 and α=0.05. Accordingly, eighty-one test specimens were grouped into nine blocks of nine specimens, with each block containing one of each colored brand. The test sequence within each block was randomized. All specimens of a given type were obtained from the same region of one 15-foot spool of chain. All specimens within a block were tested the same day.

The statistical analysis protocol was with SAS software (Version 9.2, SAS, Cary, NC). The specimen dimensions were compared among the test sample groups using ANOVA and Ryan-Einot-Gabriel-Welsch multiple range tests. K*, K′, K′′, Tan δ, and damping were compared among the test sample groups using repeated-measures ANOVA and pairwise t-tests, with frequency as the repeated factor. Pairwise t-tests compared all frequencies for each colored brand, and a standard Bonferroni correction was applied. Pairwise t-tests also compared all colored brands for each frequency, and a step-wise Bonferroni correction was applied.

RESULTS

Measurements of Chain Dimensions

Intra-class correlations for the measurements were above 0.95 for all dimensions indicating very good reliability for the operator (H.S.). Information about the dimensions of the 9 types of elastomeric chains (3 manufacturers and 3 colors from each manufacturer) are shown in Table I. Means, standard deviations, and statistical significance for comparisons of the length, thickness, inside diameter, and outside diameter are presented.

The mean length of the specimens ranged from 12.22 mm (3M silver) to 13.54 mm (GAC clear). There were significant differences among the three brands in terms of length: 3M had the shortest specimens, and GAC had the longest specimens. The lengths for GAC products had notably higher standard deviations than the lengths for the 3M and RMO products for all colors. The GAC products showed significant differences among the three colors, with black being the shortest and clear the longest.

Mean thickness ranged from 0.50 mm (all 3 RMO products) to 0.70 mm (GAC clear). The RMO chains were the thinnest with no significant differences among the colors. For the thicker 3M and GAC chains, there were significant differences among the colors within the same brand.

Mean inside diameters ranged from 1.00 mm (3M silver) to 1.31 mm (RMO silver). Mean outside diameters ranged from 2.46 mm (3M silver) to 2.96 mm (GAC black). Unlike the GAC products, the 3M and RMO chains had no significant differences in diameter among colors within the same brand.

<u>DMA Results</u>

Mean values of K*, K′, K′′, Tan δ, and damping are plotted versus the logarithm of frequency in Figures 2 - 6. The general shapes of the curves for each variable appear similar for all colors within the same brand, but they differ somewhat across brands. The K* and K′ curves are nearly linear with positive slopes. The K″ curves are non-linear, decreasing from 0.125 Hz to 0.25 Hz and increasing from 0.25 Hz to 16.0 Hz. Similarly, the Tan δ curves are non-linear, decreasing from 0.125 Hz to either 0.25 Hz or 0.5 Hz, depending on the brand,

and then increasing up to 16.0 Hz. Damping curves show exponential decay by increasing frequency.

K*, K′, and K″ were each found to have significant three-way interaction between frequency and brand and color ($p<0.001$). Tan δ had significant two-way interactions between frequency and brand ($p<0.001$) and between brand and color ($p<0.001$). When mean DMA variables were compared within each brand and color, the values for nearly all frequencies were significantly different from one another ($p<0.05$). Therefore, these comparisons are not reported.

Means, standard deviations, and statistically significant groupings of the different brands for the five DMA variables are listed in Tables II-VI. Significant differences were found for all variables and frequencies.

Table II and III show that there were no significant differences in K* and K′ among any 3M or RMO colored chains. The GAC products had significantly higher K* and K′ values than the 3M and RMO products at every frequency. At every frequency the GAC clear chain specimens had mean K* and K′ that was significantly higher than K* and K′ for the GAC silver and black chain specimens.

Table IV shows that K″ values were highest for the GAC products, with the GAC clear chains being significantly higher than GAC silver and black chains at every frequency.

Table V shows that Tan δ values ranged from 0.119 to 0.182 over all the tested frequencies. This corresponds to δ values of 6.8° to 10.3°. Overall there were multiple significant differences in Tan δ among the chain brands and colors with no general consistency across frequencies. However, at frequencies of 4.0 Hz and lower, the GAC products have the highest Tan δ.

Table VI shows Damping values that are related to K” and frequency. There were no significant brand differences at frequencies higher than 1.0 Hz. However, at lower frequencies GAC brand had significantly higher damping.

DISCUSSION

Previous studies on force delivery and force decay of elastomeric chains have shown that these physical properties can be affected by manufacturing factors.[19,21,23,28-32] The results of this DMA study show that there are clearly differences in initial dynamic force delivery and viscoelastic properties for three different brands of elastomeric chains. Differences in specimen dimensions affect structural properties, such as K*, K’ , K”, and damping. Proprietary differences in chemical composition inherent to different brands of elastomeric chains and the introduction of pigments may also contribute to differences in structural properties.

The operator's measurement reliability was very good for all four dimensions. The three different brands, and even the three different colors of GAC chains, were found to have different dimensions. Lengths increased by up to 10.8%, and chain thicknesses by up to 40.0%, across brands. Inside diameters increased by up to 31.0%, and outside diameters by up to 20.3%, across brands. These differences in specimen dimensions should also account for some observed differences in structural DMA properties.

Since all the specimen dimensions differ significantly across brands, it is difficult to isolate the effects of individual dimensions on DMA variables and thus the effects of the proprietary material compositions from purely dimension effects. Tan δ is the most likely DMA parameter to represent effects from proprietary material compositions and pigmentation since it is the quotient of the dimension-dependent K′ and K′′. Since the lower frequencies tested are more relevant to human jaw movements,[39] it is plausible that the GAC brand of color elastomeric chains could have more initial force decay than the 3M Unitek and RMO brands in a clinical setting.

Some differences were observed among colors within brands for K*, K′ and K″, especially for the GAC clear vs. GAC black and silver chains. However, all dimensions for the GAC clear chains are significantly different from those for the GAC black and silver chains, so it is difficult to isolate pigment effects. The 3M and RMO chain products have fewer dimensional differences across the three colors selected for this study, and no differences in K*, K′ ,K″, and damping were found for the three colored products from each of these manufacturers. This suggests that the three pigments selected for chain products in this study have relatively little effect on dynamic force delivery and viscoelastic behavior, and that dimensions and other proprietary material factors account for the observed differences in K*, K′ ,K″, and damping.

In orthodontics, it is highly desirable to have optimal light and constant forces on teeth to provide more efficient treatment and less frequent reactivation appointments. It is well known that currently available elastomeric chains experience force decay and do not apply constant orthodontic forces that can be easily controlled. Studying the viscoelastic properties of elastomeric chains could provide some insight to manufacturers so that improved elastomeric chains that have less viscous character and experience less force decay can be developed.

The results of this pioneering DMA study show that manufacturing factors likely combine to affect the dynamic force delivery and viscoelastic properties of elastomeric chains. It is expected that the relative rankings of the present DMA properties for the elastomeric chains studied would not have been altered if the experiments had been performed at mouth temperature rather than room temperature. Further investigations are needed to isolate the effects of individual manufacturing factors and to determine how the dynamic force delivery and viscoelastic properties of elastomeric chains relate to tooth movement.

CONCLUSIONS

The objective of this research was to compare dynamic force delivery and viscoelastic properties of different brands and colors of elastomeric chains using DMA testing. Under the conditions of this study, the following conclusions can be drawn:

1. There were significant differences in measured dimensions across the three brands. The GAC brand also had significant differences in measured dimensions across colors for the elastomeric chains. These differences likely contributed to the observed differences in dynamic force delivery and viscoelastic properties.
2. When the five mean DMA variables were compared for the elastomeric chains within each brand and color, using pairwise t-tests and a standard Bonferroni correction, the values for nearly all frequencies were significantly different from one another.

3. When the five mean DMA variables were compared for the elastomeric chains within each frequency, using pairwise t-tests and a stepwise Bonferroni correction, significant differences in dynamic force delivery and viscoelastic properties were found for all variables and most frequencies.
4. Multiple manufacturing factors likely combine to affect dynamic force delivery and viscoelastic properties of elastomeric chains. More research is needed to isolate the effects of individual manufacturing factors and to determine how the dynamic force delivery and viscoelastic properties of elastomeric chains relate to tooth movement.

ACKNOWLEDGEMENT

This study was supported by the Delta Dental Foundation.

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CHAPTER 4

CONCLUSIONS

The objective of this research was to compare dynamic force delivery and viscoelastic properties of different brands and colors of elastomeric chains using DMA testing. Under the conditions of this study, the following conclusions can be drawn:

2. There were significant differences in measured dimensions across the three brands. The GAC brand also had significant differences in measured dimensions across colors for the elastomeric chains. These differences likely contributed to the observed differences in dynamic force delivery and viscoelastic properties.

2. When the five mean DMA variables were compared for the elastomeric chains within each brand and color, using pairwise t-tests and a standard Bonferroni correction, the values for nearly all frequencies were significantly different from one another.

3. When the five mean DMA variables were compared for the elastomeric chains within each frequency, using pairwise t-tests

and a stepwise Bonferroni correction, significant differences in dynamic force delivery and viscoelastic properties were found for all variables and most frequencies.

4. Multiple manufacturing factors likely combine to affect dynamic force delivery and viscoelastic properties of elastomeric chains. More research is needed to isolate the effects of individual manufacturing factors and to determine how the dynamic force delivery and viscoelastic properties of elastomeric chains relate to tooth movement.

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APPENDIX A

TABLES

Length (mm)					Thickness (mm)				
Brand	*Color*	*Mean*	*SD*	*Groups*	*Brand*	*Color*	*Mean*	*SD*	*Groups*
3M	Silver	12.216	0.014	A	RMO	Clear	0.497	0.005	A
3M	Clear	12.233	0.030	A	RMO	Black	0.500	0.000	A
3M	Black	12.244	0.024	A	RMO	Silver	0.500	0.000	A
RMO	Silver	12.688	0.029	B	3M	Black	0.598	0.007	B
RMO	Clear	12.691	0.029	B	GAC	Silver	0.644	0.014	C
RMO	Black	12.702	0.027	B	GAC	Black	0.647	0.009	C D
GAC	Black	13.044	0.054	C	3M	Clear	0.653	0.005	C D
GAC	Silver	13.308	0.130	D	3M	Silver	0.656	0.005	D
GAC	Clear	13.544	0.136	E	GAC	Clear	0.703	0.007	E

Inside Diameter (mm)					Outside Diameter (mm)				
Brand	*Color*	*Mean*	*SD*	*Groups*	*Brand*	*Color*	*Mean*	*SD*	*Groups*
3M	Silver	1.002	0.014	A	3M	Silver	2.457	0.010	A
3M	Black	1.007	0.016	A	3M	Black	2.464	0.019	A
3M	Clear	1.014	0.029	A	3M	Clear	2.467	0.009	A
GAC	Silver	1.157	0.046	B	RMO	Silver	2.589	0.015	B
GAC	Black	1.202	0.035	B	RMO	Clear	2.609	0.020	B
GAC	Clear	1.238	0.027	C	RMO	Black	2.614	0.019	B
RMO	Clear	1.290	0.034	D	GAC	Silver	2.833	0.049	C
RMO	Black	1.294	0.025	D	GAC	Clear	2.896	0.037	D
RMO	Silver	1.310	0.024	D	GAC	Black	2.956	0.035	E

Table I. Elastomeric chain measurements [N=9 for each colored brand; means with the same group letter are not significantly different (α=0.05)]

0.125 Hz				
Brand	*Color*	*Mean*	*SD*	*Groups*
3M	Black	0.588	0.033	A
3M	Clear	0.611	0.020	A
RMO	Silver	0.615	0.035	A
RMO	Clear	0.636	0.067	A
3M	Silver	0.638	0.022	A
RMO	Black	0.639	0.050	A
GAC	Silver	0.852	0.031	B
GAC	Black	0.855	0.038	B
GAC	Clear	0.967	0.040	C

0.25 Hz				
Brand	*Color*	*Mean*	*SD*	*Groups*
3M	Black	0.617	0.034	A
RMO	Silver	0.637	0.036	A
3M	Clear	0.640	0.021	A
RMO	Clear	0.657	0.065	A
RMO	Black	0.660	0.050	A
3M	Silver	0.667	0.021	A
GAC	Silver	0.894	0.034	B
GAC	Black	0.895	0.034	B
GAC	Clear	1.015	0.040	C

0.50 Hz				
Brand	*Color*	*Mean*	*SD*	*Groups*
3M	Black	0.650	0.034	A
RMO	Silver	0.662	0.037	A
3M	Clear	0.671	0.021	A
RMO	Black	0.682	0.051	A
RMO	Clear	0.684	0.068	A
3M	Silver	0.698	0.020	A
GAC	Silver	0.936	0.033	B
GAC	Black	0.939	0.035	B
GAC	Clear	1.065	0.039	C

1.0 Hz				
Brand	*Color*	*Mean*	*SD*	*Groups*
3M	Black	0.679	0.038	A
RMO	Silver	0.687	0.038	A
3M	Clear	0.700	0.020	A
RMO	Black	0.702	0.050	A
RMO	Clear	0.707	0.067	A
3M	Silver	0.728	0.021	A
GAC	Silver	0.977	0.035	B
GAC	Black	0.978	0.037	B
GAC	Clear	1.111	0.037	C

2.0 Hz				
Brand	*Color*	*Mean*	*SD*	*Groups*
3M	Black	0.712	0.039	A
RMO	Silver	0.714	0.039	A
RMO	Black	0.728	0.051	A
3M	Clear	0.731	0.020	A
RMO	Clear	0.735	0.070	A
3M	Silver	0.761	0.021	A
GAC	Silver	1.024	0.036	B
GAC	Black	1.025	0.037	B
GAC	Clear	1.164	0.038	C

4.0 Hz				
Brand	*Color*	*Mean*	*SD*	*Groups*
RMO	Silver	0.745	0.040	A
3M	Black	0.746	0.040	A
RMO	Black	0.757	0.052	A
3M	Clear	0.767	0.021	A
RMO	Clear	0.768	0.072	A
3M	Silver	0.798	0.021	A
GAC	Silver	1.072	0.035	B
GAC	Black	1.073	0.038	B
GAC	Clear	1.219	0.039	C

8.0 Hz				
Brand	*Color*	*Mean*	*SD*	*Groups*
RMO	Silver	0.776	0.041	A
3M	Black	0.779	0.041	A
RMO	Black	0.788	0.051	A
RMO	Clear	0.800	0.074	A
3M	Clear	0.802	0.023	A
3M	Silver	0.837	0.021	A
GAC	Silver	1.121	0.036	B
GAC	Black	1.121	0.038	B
GAC	Clear	1.274	0.041	C

16.0 Hz				
Brand	*Color*	*Mean*	*SD*	*Groups*
RMO	Silver	0.814	0.042	A
3M	Black	0.821	0.043	A
RMO	Black	0.829	0.051	A
RMO	Clear	0.843	0.076	A
3M	Clear	0.847	0.022	A
3M	Silver	0.881	0.023	A
GAC	Silver	1.179	0.037	B
GAC	Black	1.180	0.041	B
GAC	Clear	1.342	0.042	C

Table II. Pairwise t-tests of dynamic stiffness [K* (N/mm)] with step-wise Bonferroni correction [N=9 for each colored brand; means with the same group letter are not significantly different ($p<0.027$)]

0.125 Hz					0.25 Hz				
Brand	*Color*	*Mean*	*SD*	*Groups*	*Brand*	*Color*	*Mean*	*SD*	*Groups*
3M	Black	0.582	0.032	A	3M	Black	0.612	0.033	A
3M	Clear	0.605	0.019	A	RMO	Silver	0.633	0.036	A
RMO	Silver	0.610	0.035	A	3M	Clear	0.635	0.020	A
RMO	Clear	0.631	0.066	A	RMO	Clear	0.652	0.065	A
3M	Silver	0.632	0.022	A	RMO	Black	0.656	0.050	A
RMO	Black	0.634	0.050	A	3M	Silver	0.662	0.021	A
GAC	Silver	0.842	0.030	B	GAC	Silver	0.885	0.033	B
GAC	Black	0.846	0.038	B	GAC	Black	0.886	0.033	B
GAC	Clear	0.956	0.040	C	GAC	Clear	1.005	0.039	C

0.50 Hz					1.0 Hz				
Brand	*Color*	*Mean*	*SD*	*Groups*	*Brand*	*Color*	*Mean*	*SD*	*Groups*
3M	Black	0.645	0.034	A	3M	Black	0.674	0.037	A
RMO	Silver	0.657	0.037	A	RMO	Silver	0.681	0.037	A
3M	Clear	0.666	0.021	A	3M	Clear	0.695	0.020	A
RMO	Black	0.678	0.050	A	RMO	Black	0.697	0.050	A
RMO	Clear	0.679	0.068	A	RMO	Clear	0.701	0.066	A
3M	Silver	0.693	0.020	A	3M	Silver	0.722	0.021	A
GAC	Silver	0.927	0.033	B	GAC	Silver	0.968	0.034	B
GAC	Black	0.930	0.035	B	GAC	Black	0.969	0.036	B
GAC	Clear	1.055	0.039	C	GAC	Clear	1.101	0.037	C

2.0 Hz					4.0 Hz				
Brand	*Color*	*Mean*	*SD*	*Groups*	*Brand*	*Color*	*Mean*	*SD*	*Groups*
3M	Black	0.706	0.038	A	RMO	Silver	0.737	0.040	A
RMO	Silver	0.708	0.039	A	3M	Black	0.739	0.039	A
RMO	Black	0.722	0.051	A	RMO	Black	0.750	0.052	A
3M	Clear	0.726	0.020	A	RMO	Clear	0.760	0.071	A
RMO	Clear	0.729	0.069	A	3M	Clear	0.760	0.021	A
3M	Silver	0.754	0.021	A	3M	Silver	0.791	0.021	A
GAC	Silver	1.014	0.035	B	GAC	Silver	1.060	0.034	B
GAC	Black	1.015	0.037	B	GAC	Black	1.061	0.038	B
GAC	Clear	1.152	0.038	C	GAC	Clear	1.205	0.039	C

8.0 Hz					16.0 Hz				
Brand	*Color*	*Mean*	*SD*	*Groups*	*Brand*	*Color*	*Mean*	*SD*	*Groups*
RMO	Silver	0.766	0.041	A	RMO	Silver	0.801	0.042	A
3M	Black	0.771	0.041	A	3M	Black	0.811	0.042	A
RMO	Black	0.780	0.051	A	RMO	Black	0.817	0.051	A
RMO	Clear	0.790	0.074	A	RMO	Clear	0.830	0.076	A
3M	Clear	0.794	0.023	A	3M	Clear	0.837	0.022	A
3M	Silver	0.828	0.021	A	3M	Silver	0.870	0.023	A
GAC	Silver	1.107	0.036	B	GAC	Silver	1.162	0.036	B
GAC	Black	1.107	0.038	B	GAC	Black	1.163	0.040	B
GAC	Clear	1.258	0.041	C	GAC	Clear	1.322	0.042	C

Table III. Pairwise t-tests of storage stiffness [K′ (N/mm)] with step-wise Bonferroni correction [N=9 for each colored brand; means with the same group letter are not significantly different ($p<0.027$)]

0.125 Hz					0.25 Hz				
Brand	*Color*	*Mean*	*SD*	*Groups*	*Brand*	*Color*	*Mean*	*SD*	*Groups*
RMO	Black	0.076	0.006	A	RMO	Black	0.072	0.006	A
RMO	Silver	0.079	0.004	B A	RMO	Silver	0.076	0.005	B A
RMO	Clear	0.080	0.011	B A	3M	Clear	0.077	0.004	B A
3M	Clear	0.081	0.005	B A	3M	Black	0.077	0.006	B A
3M	Black	0.084	0.006	B A	RMO	Clear	0.078	0.008	B A
3M	Silver	0.087	0.005	B	3M	Silver	0.083	0.004	B
GAC	Black	0.127	0.008	C	GAC	Black	0.122	0.007	C
GAC	Silver	0.128	0.008	C	GAC	Silver	0.124	0.007	C
GAC	Clear	0.147	0.008	D	GAC	Clear	0.140	0.007	D

0.50 Hz					1.0 Hz				
Brand	*Color*	*Mean*	*SD*	*Groups*	*Brand*	*Color*	*Mean*	*SD*	*Groups*
RMO	Black	0.075	0.006	A	RMO	Black	0.082	0.004	A
3M	Clear	0.081	0.004	B A	3M	Clear	0.085	0.004	A
RMO	Silver	0.082	0.005	B A	3M	Black	0.086	0.006	A
RMO	Clear	0.082	0.008	B A	RMO	Silver	0.087	0.004	A
3M	Black	0.083	0.005	B A	RMO	Clear	0.088	0.007	A
3M	Silver	0.087	0.005	B	3M	Silver	0.089	0.003	A
GAC	Black	0.127	0.007	C	GAC	Black	0.131	0.006	B
GAC	Silver	0.128	0.007	C	GAC	Silver	0.134	0.007	B
GAC	Clear	0.146	0.006	D	GAC	Clear	0.153	0.006	C

2.0 Hz					4.0 Hz				
Brand	*Color*	*Mean*	*SD*	*Groups*	*Brand*	*Color*	*Mean*	*SD*	*Groups*
RMO	Black	0.090	0.004	A	3M	Clear	0.101	0.004	A
3M	Clear	0.092	0.004	A	RMO	Black	0.101	0.005	A
3M	Black	0.093	0.006	A	3M	Black	0.102	0.005	A
RMO	Silver	0.096	0.004	A	3M	Silver	0.107	0.003	A
3M	Silver	0.097	0.003	A	RMO	Silver	0.107	0.004	A
RMO	Clear	0.097	0.008	A	RMO	Clear	0.110	0.008	A
GAC	Black	0.141	0.007	B	GAC	Black	0.155	0.005	B
GAC	Silver	0.145	0.008	B	GAC	Silver	0.158	0.008	B
GAC	Clear	0.164	0.006	C	GAC	Clear	0.180	0.007	C

8.0 Hz					16.0 Hz				
Brand	*Color*	*Mean*	*SD*	*Groups*	*Brand*	*Color*	*Mean*	*SD*	*Groups*
3M	Clear	0.114	0.005	A	3M	Black	0.130	0.006	A
3M	Black	0.114	0.006	A	3M	Clear	0.131	0.005	A
RMO	Black	0.117	0.005	B A	3M	Silver	0.137	0.003	B A
3M	Silver	0.120	0.003	B A	RMO	Black	0.139	0.004	B A C
RMO	Silver	0.124	0.005	B A	RMO	Silver	0.146	0.005	B C
RMO	Clear	0.127	0.009	B	RMO	Clear	0.149	0.010	C
GAC	Black	0.174	0.007	C	GAC	Black	0.198	0.008	D
GAC	Silver	0.176	0.008	C	GAC	Silver	0.201	0.010	D
GAC	Clear	0.202	0.008	D	GAC	Clear	0.230	0.008	E

Table IV. Pairwise t-tests of loss stiffness [K’’ (N/mm)] with step-wise Bonferroni correction [N=9 for each colored brand; means with the same group letter are not significantly different (p<0.041)]

0.125 Hz				
Brand	*Color*	*Mean*	*SD*	*Groups*
RMO	Black	0.119	0.005	A
RMO	Clear	0.127	0.005	B
RMO	Silver	0.129	0.006	B
3M	Clear	0.133	0.007	C B
3M	Silver	0.137	0.005	C
3M	Black	0.145	0.004	C
GAC	Black	0.150	0.004	D
GAC	Silver	0.152	0.005	D
GAC	Clear	0.154	0.005	D

0.25 Hz				
Brand	*Color*	*Mean*	*SD*	*Groups*
RMO	Black	0.109	0.005	A
RMO	Silver	0.120	0.005	B
RMO	Clear	0.120	0.003	B
3M	Clear	0.121	0.005	B
3M	Silver	0.126	0.005	B
3M	Black	0.127	0.006	B
GAC	Black	0.138	0.003	C
GAC	Clear	0.140	0.004	C
GAC	Silver	0.140	0.005	C

0.50 Hz				
Brand	*Color*	*Mean*	*SD*	*Groups*
RMO	Black	0.111	0.004	A
RMO	Clear	0.121	0.003	B
3M	Clear	0.122	0.004	C B
RMO	Silver	0.124	0.006	C B
3M	Silver	0.125	0.006	C B
3M	Black	0.128	0.004	C
GAC	Black	0.137	0.004	D
GAC	Silver	0.139	0.004	D
GAC	Clear	0.139	0.004	D

1.0 Hz				
Brand	*Color*	*Mean*	*SD*	*Groups*
RMO	Black	0.118	0.005	A
3M	Clear	0.123	0.005	B A
3M	Silver	0.123	0.003	B A
RMO	Clear	0.126	0.003	B
3M	Black	0.128	0.003	B C
RMO	Silver	0.128	0.004	B C
GAC	Black	0.135	0.003	D C
GAC	Silver	0.138	0.004	D
GAC	Clear	0.139	0.004	D

2.0 Hz				
Brand	*Color*	*Mean*	*SD*	*Groups*
RMO	Black	0.125	0.003	A
3M	Clear	0.127	0.004	B A
3M	Silver	0.128	0.003	B A
3M	Black	0.131	0.003	B A C
RMO	Clear	0.134	0.004	B D C
RMO	Silver	0.136	0.003	E D C
GAC	Black	0.139	0.002	E D
GAC	Silver	0.143	0.004	E
GAC	Clear	0.143	0.004	E

4.0 Hz				
Brand	*Color*	*Mean*	*SD*	*Groups*
3M	Clear	0.133	0.004	A
RMO	Black	0.135	0.004	A
3M	Silver	0.135	0.003	A
3M	Black	0.138	0.002	B A
RMO	Clear	0.145	0.005	B C
RMO	Silver	0.146	0.004	C
GAC	Black	0.146	0.002	C
GAC	Silver	0.149	0.005	C
GAC	Clear	0.149	0.004	C

8.0 Hz				
Brand	*Color*	*Mean*	*SD*	*Groups*
3M	Clear	0.143	0.005	A
3M	Silver	0.145	0.003	A
3M	Black	0.149	0.003	A
RMO	Black	0.150	0.005	B A
GAC	Black	0.157	0.002	B C
GAC	Silver	0.159	0.005	C
GAC	Clear	0.160	0.004	C
RMO	Clear	0.161	0.005	C
RMO	Silver	0.162	0.005	C

16.0 Hz				
Brand	*Color*	*Mean*	*SD*	*Groups*
3M	Clear	0.156	0.005	A
3M	Silver	0.157	0.003	A
3M	Black	0.160	0.002	A
RMO	Black	0.170	0.006	B
GAC	Black	0.171	0.003	B
GAC	Silver	0.173	0.006	C B
GAC	Clear	0.174	0.005	C B
RMO	Clear	0.180	0.006	C D
RMO	Silver	0.182	0.005	D

Table V. Pairwise t-tests of Tan δ with step-wise Bonferroni correction [N=9 for each colored brand; means with the same group letter are not significantly different ($p<0.050$)]

0.125 Hz						
Brand	*Color*	*Mean*	*SD*	*Groups*		
RMO	Black	0.0962	0.0072		A	
RMO	Silver	0.1000	0.0056	B	A	
RMO	Clear	0.1021	0.0134	B	A	C
3M	Clear	0.1026	0.0062	B		C
3M	Black	0.1069	0.0077		D	C
3M	Silver	0.1102	0.0063		D	
GAC	Black	0.1615	0.0097		E	
GAC	Silver	0.1628	0.0098		E	
GAC	Clear	0.1870	0.0107		F	

0.25 Hz					
Brand	*Color*	*Mean*	*SD*	*Groups*	
RMO	Black	0.0455	0.0036		A
RMO	Silver	0.0482	0.0032	B	A
3M	Clear	0.0486	0.0024	B	A
3M	Black	0.0492	0.0040	B	A
RMO	Clear	0.0498	0.0053	B	A
3M	Silver	0.0528	0.0023	B	
GAC	Black	0.0775	0.0042		C
GAC	Silver	0.0787	0.0046		C
GAC	Clear	0.0892	0.0043		D

0.50 Hz					
Brand	*Color*	*Mean*	*SD*	*Groups*	
RMO	Black	0.0246	0.0019		A
3M	Clear	0.0265	0.0011		A
RMO	Silver	0.0266	0.0016		A
RMO	Clear	0.0266	0.0027		A
3M	Black	0.0270	0.0017		A
3M	Silver	0.0282	0.0017		A
GAC	Black	0.0414	0.0024		B
GAC	Silver	0.0418	0.0022	C	B
GAC	Clear	0.0477	0.0019	C	

1.0 Hz				
Brand	*Color*	*Mean*	*SD*	*Groups*
RMO	Black	0.0131	0.0006	A
3M	Clear	0.0136	0.0006	A
3M	Black	0.0137	0.0009	A
RMO	Silver	0.0139	0.0007	A
RMO	Clear	0.0141	0.0012	A
3M	Silver	0.0142	0.0005	A
GAC	Black	0.0208	0.0010	B
GAC	Silver	0.0213	0.0011	B
GAC	Clear	0.0243	0.0009	B

2.0 Hz				
Brand	*Color*	*Mean*	*SD*	*Groups*
RMO	Black	0.0072	0.0003	A
3M	Clear	0.0073	0.0003	A
3M	Black	0.0074	0.0005	A
RMO	Silver	0.0077	0.0003	A
3M	Silver	0.0077	0.0003	A
RMO	Clear	0.0078	0.0006	A
GAC	Black	0.0113	0.0005	A
GAC	Silver	0.0115	0.0006	A
GAC	Clear	0.0131	0.0005	A

4.0 Hz				
Brand	*Color*	*Mean*	*SD*	*Groups*
3M	Clear	0.0040	0.0002	A
RMO	Black	0.0040	0.0002	A
3M	Black	0.0041	0.0002	A
3M	Silver	0.0043	0.0001	A
RMO	Silver	0.0043	0.0002	A
RMO	Clear	0.0044	0.0003	A
GAC	Black	0.0062	0.0002	A
GAC	Silver	0.0063	0.0003	A
GAC	Clear	0.0072	0.0003	A

8.0 Hz				
Brand	*Color*	*Mean*	*SD*	*Groups*
3M	Clear	0.0023	0.0001	A
3M	Black	0.0023	0.0001	A
RMO	Black	0.0023	0.0001	A
3M	Silver	0.0024	0.0001	A
RMO	Silver	0.0025	0.0001	A
RMO	Clear	0.0025	0.0002	A
GAC	Black	0.0035	0.0001	A
GAC	Silver	0.0035	0.0002	A
GAC	Clear	0.0040	0.0002	A

16.0 Hz				
Brand	*Color*	*Mean*	*SD*	*Groups*
3M	Black	0.0013	0.0001	A
3M	Clear	0.0013	0.0000	A
3M	Silver	0.0014	0.0000	A
RMO	Black	0.0014	0.0000	A
RMO	Silver	0.0014	0.0000	A
RMO	Clear	0.0015	0.0001	A
GAC	Black	0.0020	0.0001	A
GAC	Silver	0.0020	0.0001	A
GAC	Clear	0.0023	0.0001	A

Table VI. Pairwise t-tests of damping [C (N·s/mm)] with step-wise Bonferroni correction [N=9 for each colored brand; means with the same group letter are not significantly different ($p<0.027$)]

APPENDIX B

FIGURES

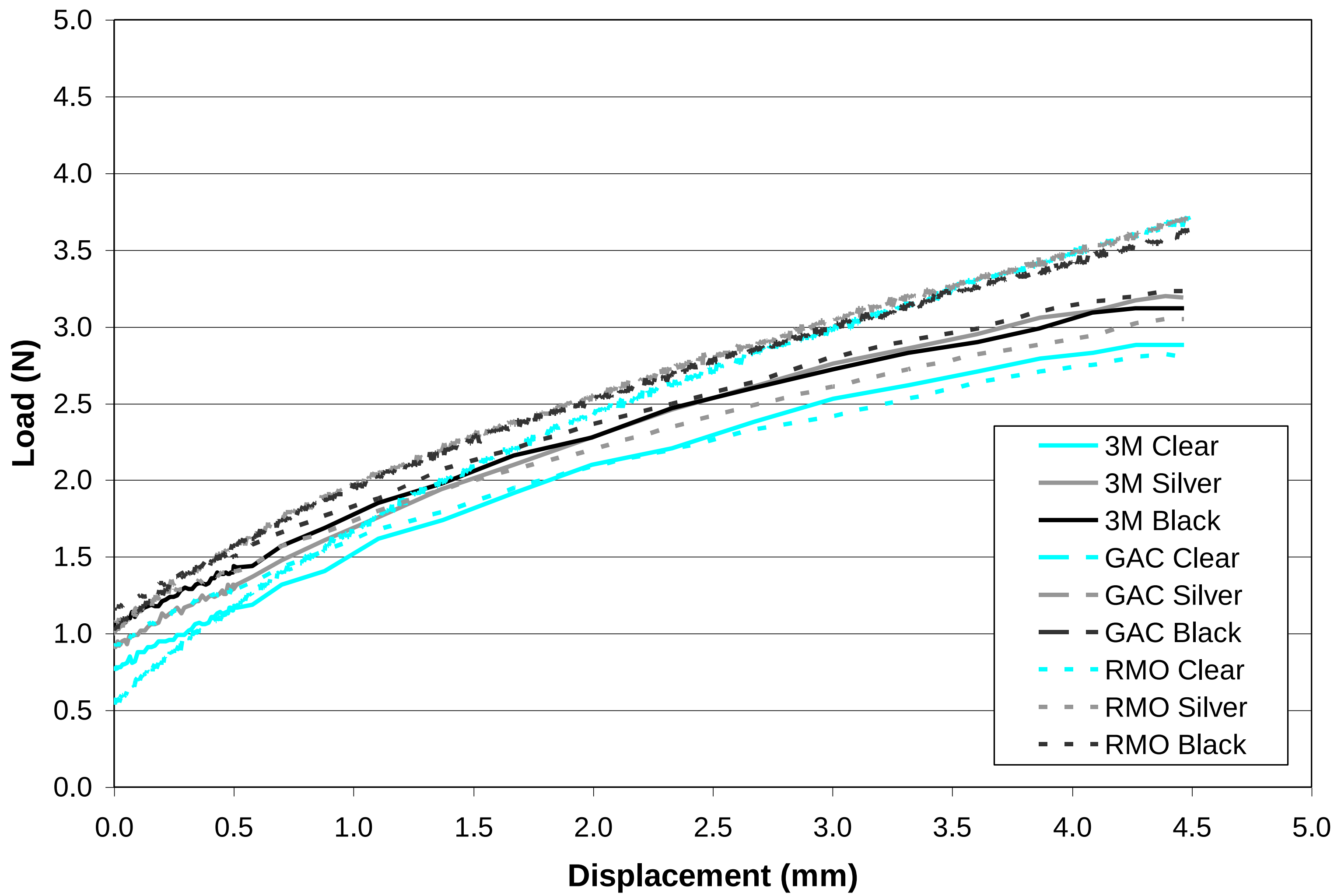

Figure 1. Load vs. displacement for all brands and colors

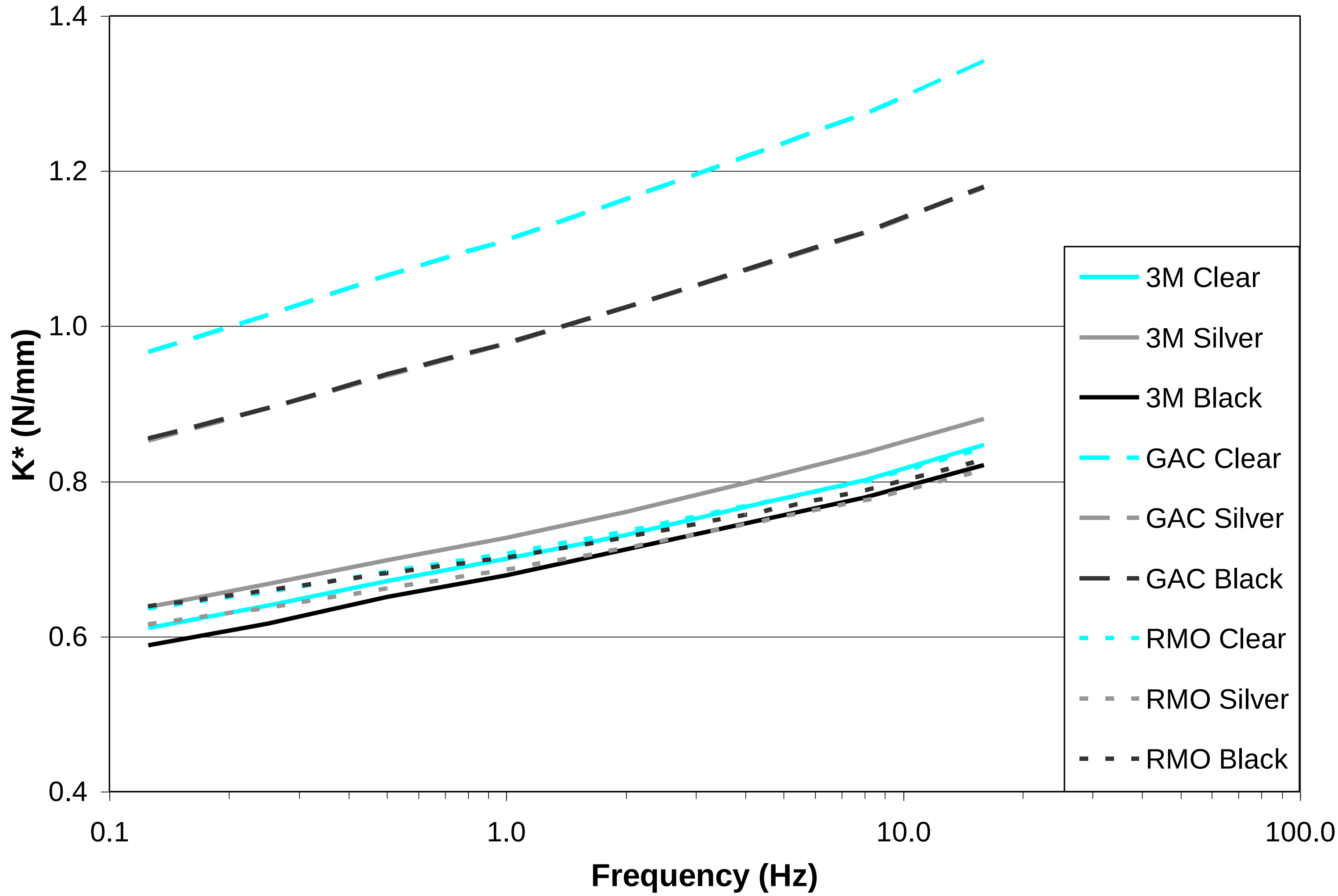

Figure 2. Mean dynamic stiffness vs. frequency for all brands and colors

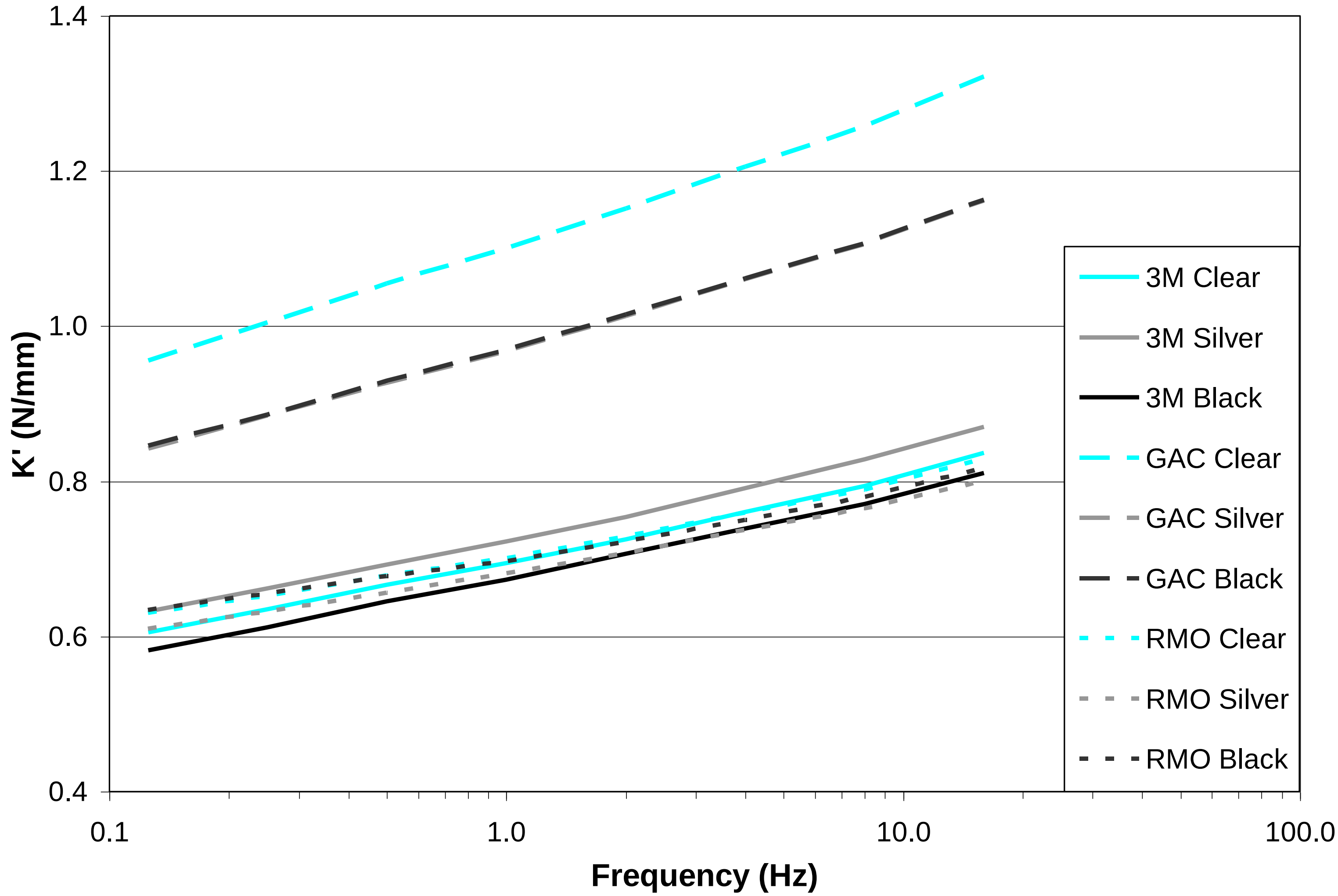

Figure 3. Mean storage stiffness vs. frequency for all brands and colors

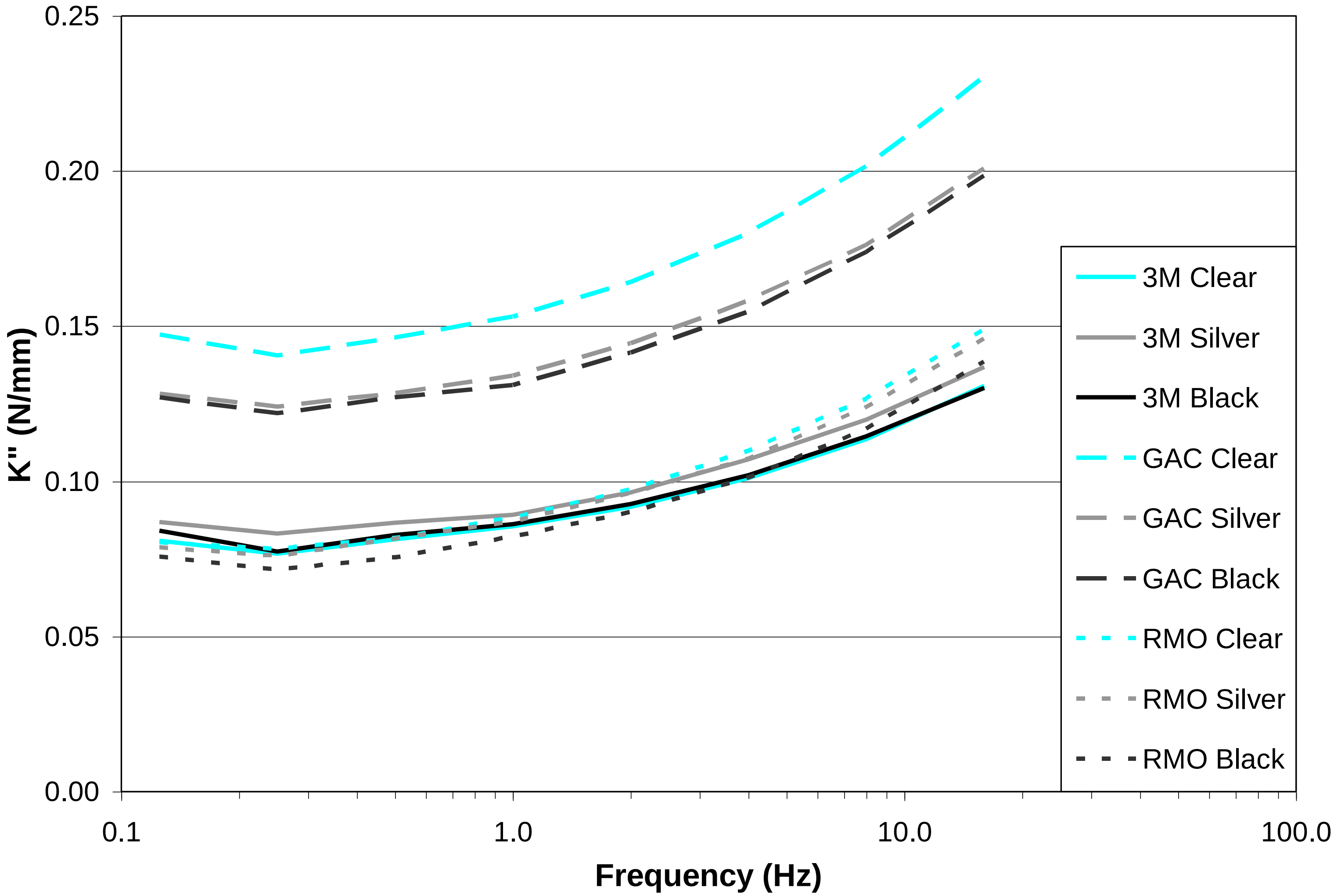

Figure 4. Mean loss stiffness vs. frequency for all brands and colors

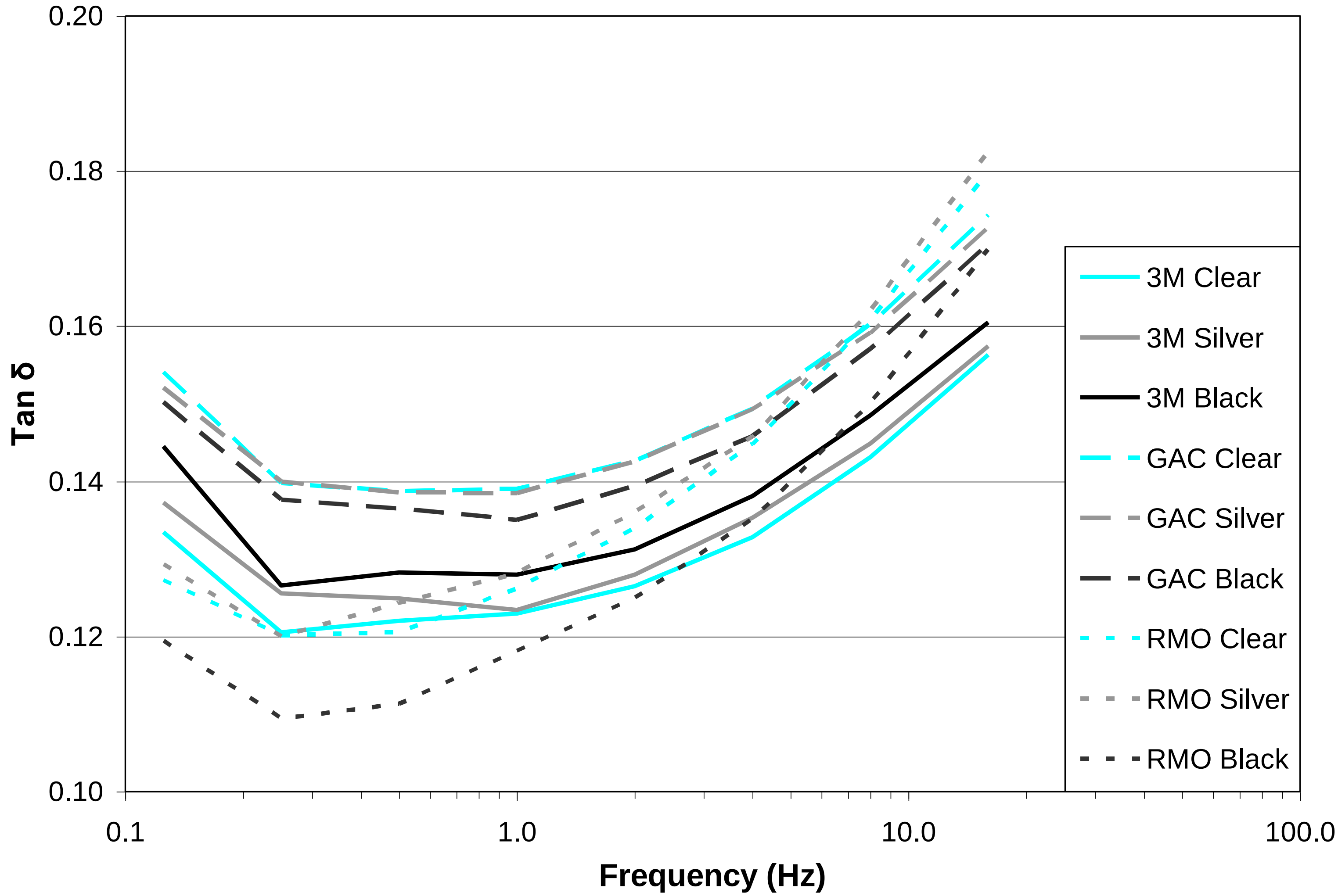

Figure 5. Mean Tangent of δ vs. frequency for all brands and colors

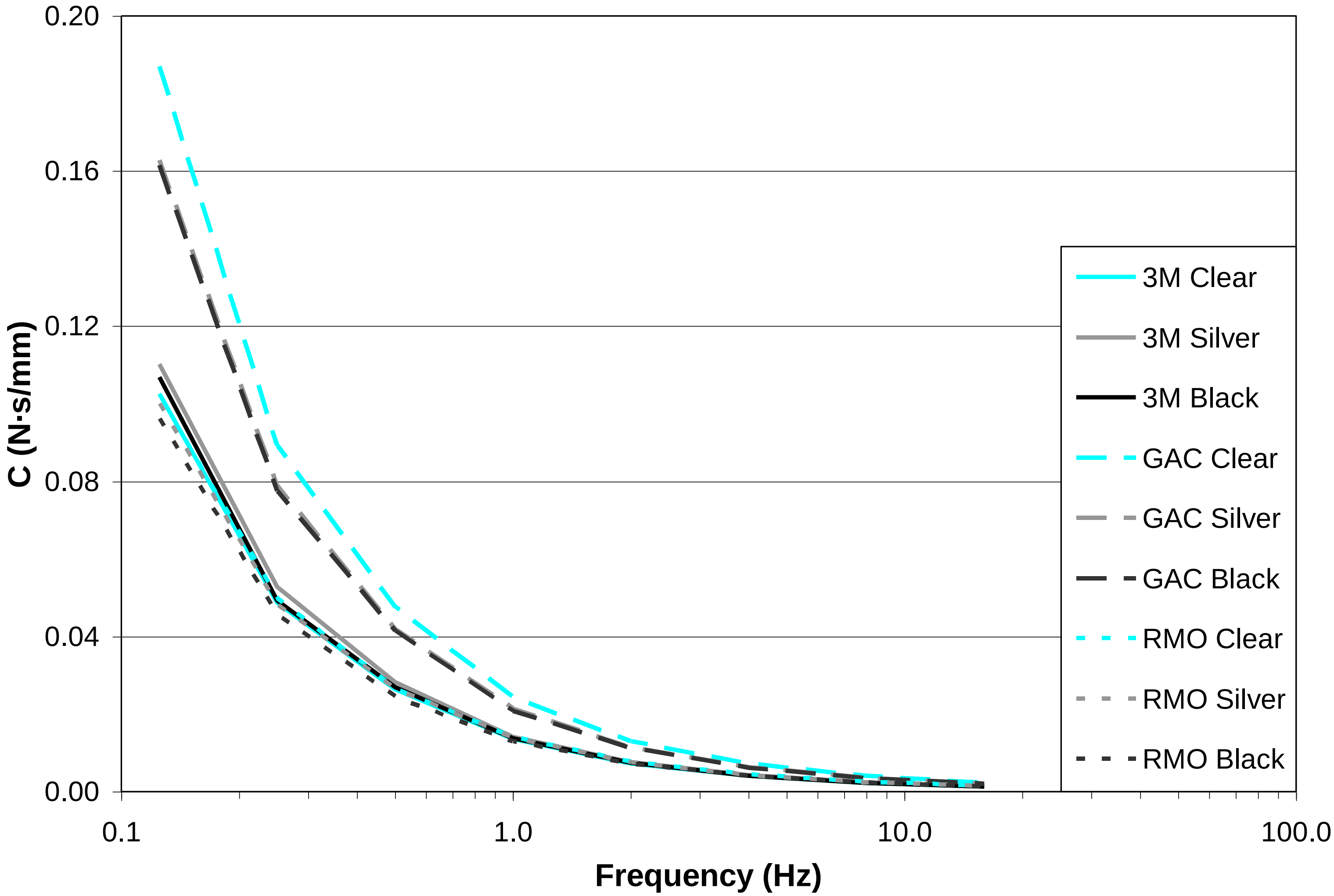

Figure 6. Mean damping vs. frequency for all brands and colors