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ORIGINAL ARTICLE

EFFECT OF PIGMENTATION ON FORCE DEGRADATION IN ORTHODONTIC ELASTOMERIC CHAINS: AN EXPERIMENTAL STUDY

Efecto de la pigmentación sobre la degradación de la fuerza en cadenas elastoméricas de ortodoncia: un estudio experimental

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ABSTRACT

Introduction: Elastomeric chains are widely used in orthodontics but struggle to maintain consistent force over time, with significant force reduction occurring shortly after application. This study aimed to compare force degradation, morphology, and chemical composition between pigmented and non-pigmented continuous elastomeric chains.

Material and Methods: Three groups (grey, red, transparent) were subjected to 150 g initial tension and immersed in artificial saliva for varying durations (30 minutes, 24 hours, 28 days), then tested using a universal machine. Structural analysis via scanning electron microscopy (SEM) and chemical analysis via Fourier transform infrared spectroscopy (FTIR) were conducted.

Results: Significant strength loss in pigmented chains compared to transparent ones occurred. After 24 hours and 28 days, grey chains showed the highest loss (25.2% and 28.1%), followed by red chains (17.9% and 21.2%), with transparent chains exhibiting the least (10.6% and 14.6%) (p<0.05). Grey chains also displayed pronounced surface changes as assessed by SEM, while FTIR revealed characteristic polyurethane bands. Despite their higher strength retention, non-pigmented chains are less popular due to patient preference.

Conclusions: Pigmented orthodontic chains exhibit significantly greater mechanical degradation and surface alterations after artificial saliva exposure than transparent chains, indicating that pigmentation adversely affects long-term strength.

Keywords: *Elastomeric polymer; Polyurethanes; Orthodontics; Tensile strength; Fourier transform infrared spectroscopy; Scanning electron microscopy*

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RESUMEN

Introducción: Las cadenas elastoméricas se utilizan ampliamente en ortodoncia, pero presentan dificultades para mantener una fuerza constante a lo largo del tiempo, con una reducción significativa de la fuerza poco después de su aplicación. Este estudio tuvo como objetivo comparar la degradación de la fuerza, la morfología y la composición química entre cadenas elastoméricas continuas pigmentadas y no pigmentadas.

Material y Métodos: Tres grupos (gris, rojo y transparente) se sometieron a una tensión inicial de 150 g y se sumergieron en saliva artificial durante diferentes periodos (30 minutos, 24 horas y 28 días). Posteriormente, se probaron con una máquina universal. Se realizó un análisis estructural mediante Microscopía electrónica de barrido (SEM) y un análisis químico mediante espectroscopía infrarroja por transformada de Fourier (FTIR).

Resultados: Se observó una pérdida significativa de resistencia en las cadenas pigmentadas en comparación con las transparentes. Después de 24 horas y 28 días, las cadenas grises mostraron la mayor pérdida (25,2% y 28,1%), seguidas de las cadenas rojas (17,9% y 21,2%), y las cadenas transparentes la menor (10,6% y 14,6%) (p<0,05). Las cadenas grises también mostraron cambios superficiales pronunciados, según la evaluación mediante SEM, mientras que la FTIR reveló bandas características de poliuretano. A pesar de su mayor retención de resistencia, las cadenas no pigmentadas son menos populares debido a la preferencia de los pacientes.

Conclusiones: Las cadenas de ortodoncia pigmentadas presentan una degradación mecánica y alteraciones superficiales significativamente mayores tras la exposición a saliva artificial que las cadenas transparentes, lo que indica que la pigmentación afecta negativamente a la resistencia a largo plazo.

Palabras clave: *Polímero elastomérico; Poliuretanos; Ortodoncia; Resistencia a la tracción; Espectroscopía infrarroja por transformada de Fourier; Microscopía electrónica de rastreo.*

INTRODUCTION

Elastomeric chains, particularly power chains, have become a prevalent system for space closure in orthodontics. This popularity stems from their ability to apply gentle, continuous forces, coupled with high flexibility and ease of use, making them readily adaptable for individual patient needs. However, it is worth noting that their mechanical effectiveness has certain limitations.[1,2] and can be influenced by material composition, external morphology, and production methods.[1]

They are composed of low molecular weight polymers structured in a complex way, organized of multiple long carbon chains loosely intertwined in a spiral fashion, with a very weak attraction consisting of primary and secondary bonds, such a configuration gives them elasticity. As the chains are extended, the primary bonds unfold in a linear and orderly fashion at the expense of the secondary bonds. The primary bonds are held together depending on the applied force. If this force exceeds their elastic limit, the primary bonds break and there will be a deformation in the chain.[3]

Therefore, the main drawback of these chains is permanent distortion, which leads to alterations of the mechanical properties, color changes and surface breakage.

Force degradation remains a major concern for clinicians, as optimal, light, continuous force is critical to achieve physiological tooth movement,[4] so several studies have been conducted to compare both force magnitude and force degradation over time.[3] The weakening of strength occurs gradually over time, influenced by factors like the shifting of neighboring molecular chains and their enduring distortion.

This degradation is linked to exposure within the oral cavity, including temperature, humidity, enzymatic activity, and the individual's dietary habits.[5,6] As a result, some researchers have analyzed this decrease in strength, finding that 50-75% of strength is lost after the first 24 hours of use[7] and this decrease continues at a steady rate.[8-11]

Furthermore, it has been observed that the strength properties of pigmented chains are significantly affected by the materials used to pigment them,[12,13] which is why some authors suggest that the addition of pigments may alter the molecular configuration causing steric interference resulting in a greater loss of strength.[3]

Considering the significant clinical implications associated with the widespread utilization of these materials, understanding the factors that impede their initial strength and contribute to strength decline during use is of paramount importance. Currently, there is limited research analyzing the impact of pigments on chain elastics.

Consequently, this study aims to address this gap and compare the loss of strength between pigmented and non-pigmented continuous elastomeric chains.

The hypothesis was that the addition of pigments may result in a more substantial loss of strength in continuous elastomeric chains compared to non-pigmented ones.

MATERIALS AND METHODS

Tensile tests and strength loss

Pigmented (grey and red, n=61, each group) and non-pigmented (transparent, n=61) closed elastomeric chains from American Orthodontics (Sheboygan, WI, USA) were used. The elastomeric chains were precisely sectioned into segments of five links using medium cutting pliers (Falcon Orthoclever).

Each segment was subjected to controlled tension by fixing the three central links at a standardized distance of 12 mm. This setup was achieved using custom-made clamps fabricated from 0.045" stainless steel wire and secured with a Mathieu clamp (Hu-Friedy). The selection of five-link segments ensured sufficient length for consistent tensioning while minimizing variability due to elongation at the terminal links. The 12 mm interlink distance was chosen based on clinically relevant activation values and to reproduce a moderate and consistent initial force, allowing for standardized comparison across samples and ensuring methodological reproducibility.

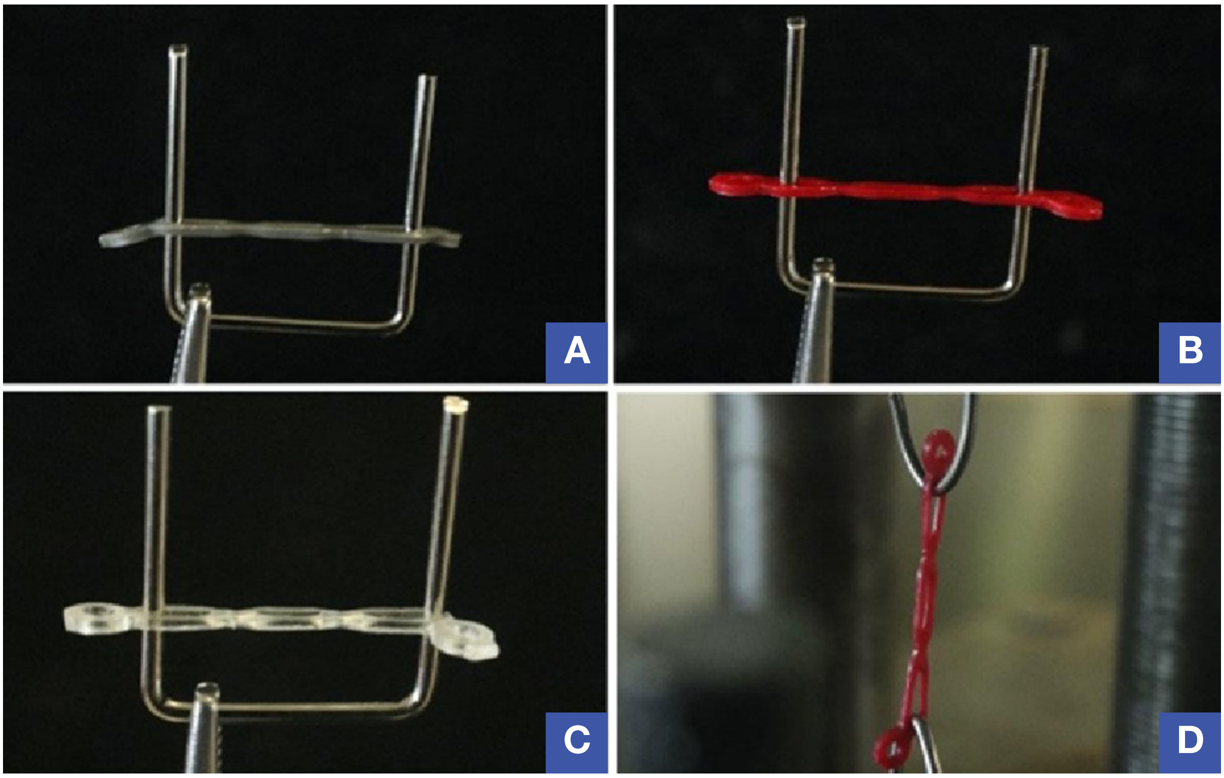
The units were immersed in artificial saliva (Prodentmex, Viarden) contains mineral chlorides (sodium, potassium, magnesium, and calcium), a non-ionic thickening agent such as hydroxypropyl methylcellulose, a humectant (*e.g.*, glycerol or sorbitol), and an enzymatic antimicrobial component such as lysozyme chloride at a concentration of 0.2–0.6% w/v. The samples were incubated in a thermal shaker (Vortemp 1550, Labnet) set at 180 rpm and 37°C for 30 minutes, 24 hours, and 28 days, corresponding to short-, medium-, and long-term exposure periods designed to simulate clinical intraoral conditions. The temperature of 37°C was selected to replicate average human body temperature, ensuring physiological relevance in the degradation and force retention behavior of the elastomeric chains. The use of agitation at 180 rpm mimics the dynamic oral environment by maintaining homogeneity of the artificial saliva and enhancing contact between the solution and the sample surface.

After each incubation period, the elastomeric units were carefully removed from the metal clamps and subjected to tensile testing at a standardized extension of 18 mm using a universal testing machine. This tensioning distance reflects a clinically relevant activation length for orthodontic elastomeric chains, allowing assessment of their mechanical performance under conditions that closely approximate actual usage. The mean force in Newtons was recorded with the digital torque indicator MECMESIN A.F.T.I. (Advanced force/torque indicator). The control group for the baseline measurement was neither tensioned in the metal clamps nor submerged in artificial saliva. These samples were directly placed into the universal testing machine directly from the packaging and were subjected to the 18 mm tension test (Figure 1).

Scanning electron microscopy (SEM)

In order to evaluate the morphological surface changes resulting from the loss of strength in the chains after the 28-day stress tests, the samples were gold-coated and analyzed under the scanning electron microscope (SEM JEOL-JSM-IT500) at 50x, 500x, 1000x and 2,500x magnifications, using

Figure 1
Tensile test links



A, B and C: Show the units were divided into 5-link chains, which were tensioned at 12 mm between the three central links in clamps made of 0.045" stainless steel wire. **D:** Indicates the tension in a universal testing machine at 18 mm.

primary electrons accelerated to 50 kV. The chain control group was included without elastic deformation.

Fourier Transform Infrared Spectroscopy (FTIR) analysis

To conduct structural and chemical analysis, three samples from the 28-day group were randomly chosen for FTIR analysis under stress and saliva immersion. The FTIR-ATR spectrum of the samples was recorded with Spectrum Two FT-IR Spectrometer (PekinElmer, Shelton, Connecticut, USA). The spectra were collected from 2000 to 600 cm^{-1} in attenuated diffuse reflectance, 10 scans with a spectral resolution of 4 cm^{-1}. The unaltered chains' control group was incorporated for comparative analysis.

Statistical analysis

The mean and standard deviation were computed, and normality was evaluated using the Shapiro-Wilk´s test. Sub-sequently, one-way ANOVA and Tukey's post hoc statistical tests were performed using the IBM SPSS 20.0 statistical package. Significance was set at $p<0.05$, with a confidence interval of 95%. The sample size per group was determined through a priori power analysis to detect significant differences with a statistical power of 80% and an alpha level of 0.05.

RESULTS

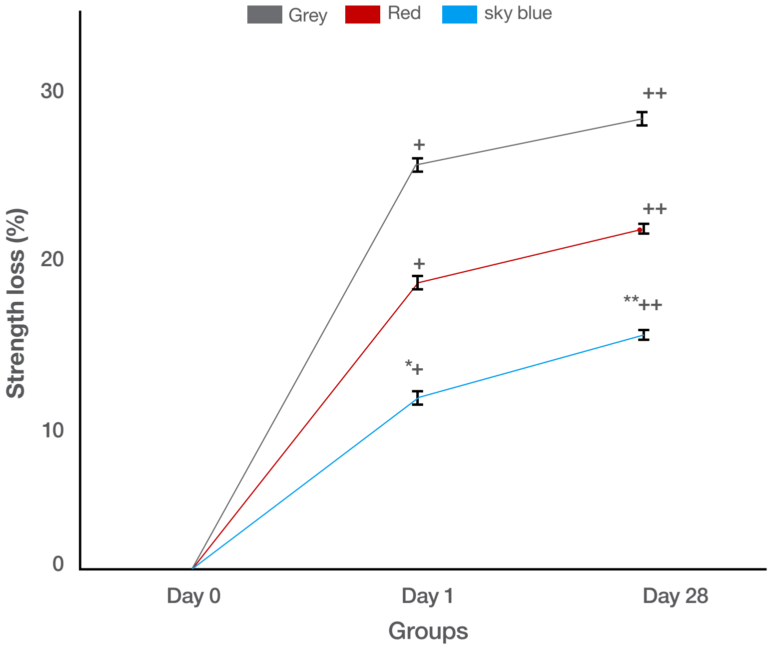
Tensile tests and strength loss

The results of the basal measurement (30 minutes) showed that all elastomeric continuous chains had similar initial strength independent of the presence or absence of pigments, with no significant intergroup difference ($p>0.05$) (Table 1).

After 24 hours of being stressed (Day 1), the grey chains experienced the highest loss of strength (25.2%), followed by the red chains

Figure 2

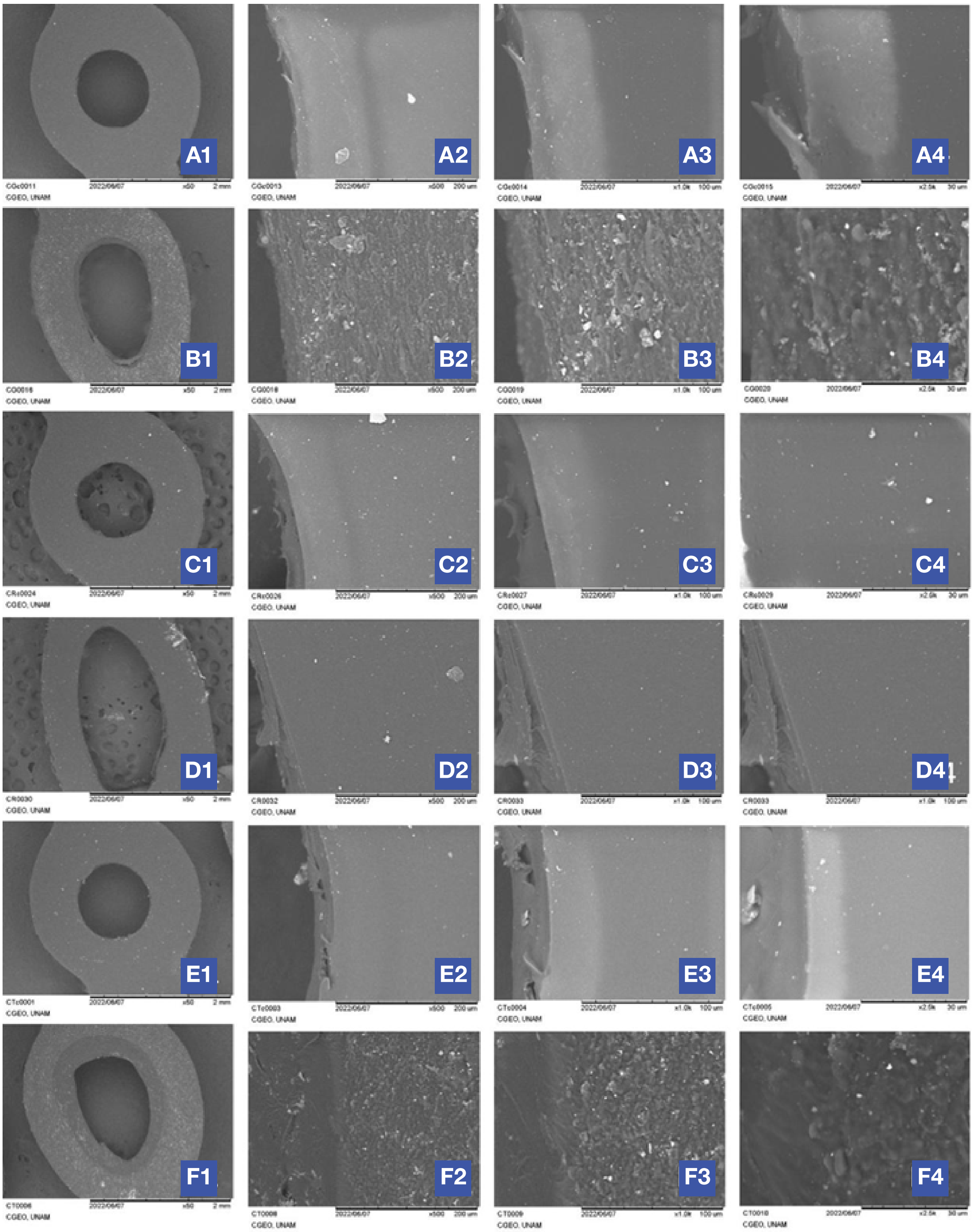
Strength loss in elastomeric chains



Data represent mean and standard deviation of loss of strength at 0, 1 and 28 days.
ANOVA test *$p<0.05$, **$p<0.05$ (Intergroup) +$p<0.05$, ++$p<0.05$ (Intragroup) Tukey's Pos hoc, n=61.

Figure 3

Tensile test links



A: Grey chain taken directly from the packaging. **B:** Grey chain under tension for 28-days. **C:** Red chain taken directly from the packaging. **D:** Red chain under tension for 28-days. **E:** Transparent chain taken directly from the packaging. **F:** Transparent chain under tension for-28 days.
The numbers represent the magnification at which the samples were observed, 1= 2mm (50x), 2= 200 µm (500x), 3= 100 µm (1000x) and 4= 50 µm (2500x).

(17.9%), transparent chains representing the lowest loss (10.6%) with statistically significant inter and intra-group difference ($p<0.05$). On day 28, the percentage of strength loss was highest in the grey chains group with 28.1 %, in the transparent chains group the lowest strength loss was identified with a decrease of 14.6 % representing a statistically significant inter- and intra-group difference ($p<0.05$) (Figure 2).

Scanning electron microscopy (SEM)

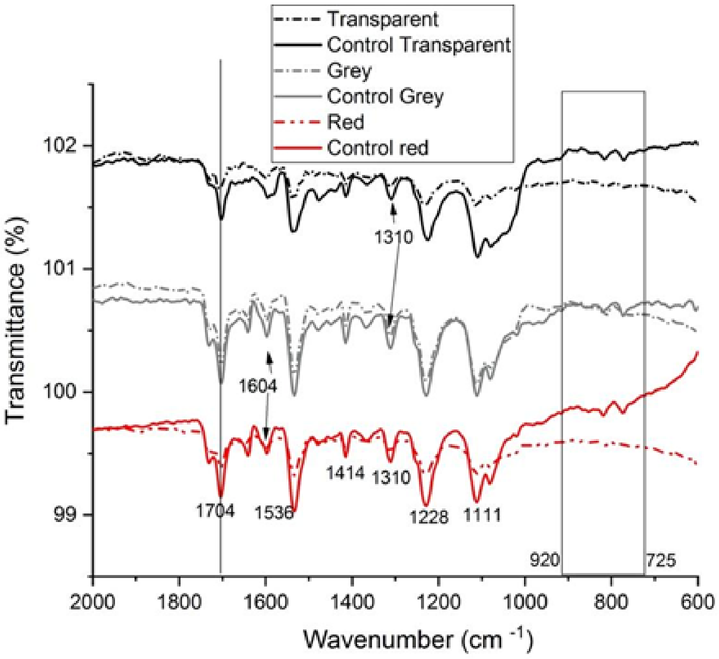
Figure 3 displays the morphological features of the chains prior to tensioning (A1, C1, and E1). Following 28-days of tension, the grey chains exhibited pronounced morphological surface changes (B1-B4), displaying microporosity and conspicuous holes in the elastomeric surface topography.

Fourier Transform Infrared Spectroscopy (FTIR) analysis

The infrared spectrum of the examined samples (Figure 4) revealed distinctive vibrational bands characteristic of polyurethane, including the carbonyl urethane group (-C=O) and the carbamate group (-CN and -C-O-C),[14] predominant in the elastic material of the studied brand. The presence of the 1536 cm^{-1} band confirms the symmetric bending vibration corresponding to the N-H isocyanate group; the bands present at 1704 cm^{-1} and 1221 cm^{-1}, are symmetric stretching vibrations of -C=O ester groups belonging to: N-CO-O,

Figure 4

Fourier Transform Infrared Spectroscopy (FTIR) analysis



Graphical representation of transmittance in percent (T%) *versus* IR frequency in wavelength (cm^{-1}) of the spectrum of the power chains analyzed

Table 1
Strength loss in continuous elastomeric chain (Newtons)

	Day 0	Day 1	Day 28
Grey	0 ± 0.3	$25.2 \pm 0.6^{+}$	$28.1 \pm 0.4^{++}$
Red	0 ± 0.2	$17.9 \pm 0.5^{+}$	$21.2 \pm 0.3^{++}$
Transparent	0 ± 0.3	$10.6 \pm 0.4^{*+}$	$14.6 \pm 0.3^{**++}$

Data represent mean and standard deviation of loss of strength at 0, 1 and 28 days. ANOVA test *$p<0.05$, **$p<0.05$ (Intergroup) +$p<0.05$, ++$p<0.05$ (Intragroup) Tukey's pos hoc, n=61

respectively. The band at 1604 cm^{-1} is caused by the C=C vibration due to the benzene ring, the small vibrations in the region 725-920 cm^{-1} correspond to out-of-plane bending vibrations belonging to the C-H group of the multisubstituted benzene ring.[15, 16]

All chains displayed significant intensity vibrational bands decreased after tension. In in the case of the transparent elastics, this decrease was greatest for the bands at 1705 cm^{-1} and 1221 cm^{-1} corresponding to symmetric stretching vibrations characteristic of the -C=O ester groups, and asymmetric C-O stretching vibrations belonging to: N-CO-O, the band 1111 cm^{-1}, is due to the symmetric stretching vibration of the free urethane ester group (N-CO-O).

DISCUSSION

Force degradation in elastomeric chains remains a significant clinical challenge in orthodontics. This study provides evidence on how pigments negatively influence strength retention, by integrating mechanical, morphological (SEM) and spectroscopic (FTIR) testing, unlike previous studies evaluating residual strength, this research addresses force degradation with surface structural alterations and molecular modifications detected by FTIR. This multidimensional approach allows for a more robust interpretation of the impact of pigments on the physical properties of the chains.

The magnitude of force and the duration of activation play crucial roles in the degradation of force within an elastic chain. According to Moghaddam *et al.*,[17] Abass *et al.*,[18] and Stroede **et al.**,[19] the extent and duration of load application impact the reduction in force. Determining the optimal force for orthodontic space closure is a subject of controversy, with estimates varying from 100 g to 300-350 g.[20,21]

Given this variability, our study chose to standardize the force across all samples. We maintained a consistent distance of 12 mm between the three central links to apply a force of approximately 150 g, which allowed a reliable comparison between groups, reinforcing the validity of the findings. In relation to pigments, a comparative study by Andhare *et al.*,[22] examining transparent and grey elastic chains, they noted that transparent chains exhibited a higher percentage of remaining strength, a finding consistent with our current study where transparent chains demonstrated greater stability. This observation aligns with broader research trends, as some researchers have analyzed the decrease in strength in elastic chains, reporting a substantial loss of 50-75% within the initial 24 hours of use.[7,11]
Moreover, this decline persists at a steady rate over time, mirroring the patterns of force reduction observed in both this study and our present investigation.

The key finding, that transparent chains show lower strength loss compared to pigmented chains, particularly gray ones, suggests that color additives may induce steric alterations that negatively affect the molecular configuration of polyurethane. This hypothesis is supported by a higher surface deformation observed by SEM in gray chains, characterized by porosity and microfractures, and by a lower spectral alteration in the functional groups of the polyurethane according to FTIR analysis. Contrarily, Chimenti *et al.,*[23] found that grey elastic chains exhibited a prolonged retention of strength compared to transparent counterparts.

Interestingly, the grey chain group initially displayed significantly higher strength than both the red and transparent groups in basal measurements. Although the grey group maintained the highest residual strength after the 28-day period, it also exhibited the greatest percentage of strength loss, reaching approximately 32%, compared to 24% in the red group and 20% in the transparent group. This indicates that, despite its superior short-term performance, the grey material under-went the most substantial degradation over time. This discrepancy suggests that, despite the initial strength advantage, transparent chains exhibit a more stable behavior over the course of extended tension. These contrasting findings highlight the nuanced interplay of factors influencing elastic chain behavior and the need for comprehensive analysis in understanding their performance dynamics. This finding is clinically relevant, as it could influence the selection of the color of the chains, beyond esthetic criteria.

Additionally, microscopic images revealed substantial differences in material surface area between stressed and unstressed chains, with grey chains displaying the greatest deformation and red chains exhibiting the opposite behavior.[24,25] This underscores the complex interplay of factors influencing elastic chain behavior, with material composition and deformation patterns contributing to the overall observed differences in strength maintenance.

The infrared spectrum of the analyzed samples showed that it is a polyurethane due to the presence of the main peaks characteristic of this polymer. According to the literature, the functional groups that we expect to find in the spectrum are the functional group C=O at an approximate transmittance peak of 1730 cm^{-1}; C=C at an approximate peak of 1520 cm^{-1}; N=C=O at 2270 cm^{-1} and C-O-C at approximately 1220 cm^{-1}.[14] Eliades *et al.,*[4] mention that the degradation of polyurethanes involves firstly the degradation of the ester groups, then the free urethane ester groups, the hydrogen bonded urethane ester groups and the urea groups. From the above, we can infer that the transparent chains are those that suffer the greatest degradation after elongation with respect to the other two groups of chains, while the grey chains show the least degradation, as the intensities of the vibrational bands for this sample show the smallest difference.[24,25] This study reveals that the transparent chains exhibited a notable reduction in the intensity of vibrational bands after tension. In the case of transparent elastics, this decrease was most pronounced for bands associated with the chains having the lowest vibrational loss of strength after the experiment.

It is important to note that this phenome--non occurred despite the grey chains having a higher initial strength. Considering this information, the study shows that, at the molecular level, the functional groups most affected by elongation and immersion in artificial saliva are the esters and free urethanes. The transparent chains, presenting a greater reduction in the intensity of the vibrational bands, could be more exposed to the action of the oral environment, despite their better overall mechanical behavior. This could be related to a lower structural interference due to the absence of pigments, allowing a more homogeneous distribution of the mechanical stress. The mechanisms causing the strength loss in elastomeric chains are multifaceted. Triwardhani *et al.*,[13] identified two manufacturing methods: diecutting and injection molding. Prior research indicated that diecut elastomeric chains exhibit higher residual strength compared to those produced via injection molding.[26]

In this study, the manufacturer's technical data sheet does not specify the manufacturing technique used for the investigated chains, emphasizing the importance of including such details in technical documentation for improved selection of elastomeric chains by practitioners.

Indeed, humidity and temperature are acknowledged factors influencing the mechanical properties of this material.[27] Eliades *et al.*,[4] and Issa *et al.*,[28] argue that the existing components in saliva can act as plasticizing agents, impacting elastic deformation, while low temperatures similarly affect this polymer. Considering this, artificial saliva was chosen for the experiment, immersing the samples within a thermal agitator maintaining a temperature of 37°C, representative of the average oral environment temperature.

In this sense, the reduction in elasticity observed in polyurethane bonds can be attributed to two primary factors. Firstly, it results from the elongation force to which the material is subjected. Secondly, the interaction with saliva plays a significant role. Polyurethane polymer chains tend to absorb water molecules present in saliva, and the hydrogen atoms permeate the polymer structure due to the negative charge of oxygen atoms. This interaction causes hydrogen ions and oxygen to form bonds, leading to microscopic swelling of the polyurethane. Consequently, this swelling contributes to a decrease in the vibration of bonds within the functional groups.[29,30]

Finally, despite showing greater signs of molecular degradation, the transparent chains demonstrated superior long-term performance, suggesting a more uniform stress distribution in the absence of pigment-related steric hindrance. Furthermore, combining SEM and FTIR provides a broader view of elastomer degradation. Despite these findings, the study has some limitations, for example, the analysis of a single brand limits the generalizability of the results, as differences in formulations between manufacturers may influence them. Furthermore, although the *in vitro* model was designed to simulate intraoral conditions, it cannot fully replicate the complex dynamics of the oral environment, such as pH fluctuations, mechanical stress of mastication or patient habits. At last, the pigment composition was not chemically characterized in this study, which restricts the interpretation of specific additives.

Therefore, future studies are needed to investigate the chemical nature of specific pigments and their interaction with matrices, in order to optimize the clinical performance and longevity of these materials.

CONCLUSIONS

Unpigmented elastomeric chains exhibit superior mechanical stability, with significantly less force degradation than their pigmented counterparts. Clear chains retained the highest percentage of initial strength, whereas grey chains, despite having a significantly higher initial strength, showed the greatest percentage of strength loss over time.

This study shows that strength loss in elastomeric chains is not just due to pigmentation, but is caused by a complex interaction of factors. These include polymer chemistry, pigment-induced steric interference and molecular degradation pathways, which were identified through FTIR analysis.

The clinical relevance lies in recognizing that elastomeric chain performance is influenced by a combination of factors, including manufacturing technique, oral pH, saliva composition and specific patient behaviours. Recognising these influences at the molecular level is vital for optimizing the clinical use of dental materials and predicting long-term mechanics in orthodontics.

CONFLICT OF INTERESTS

The authors declare there are no conflicts of interest related to this study.

ETHICS APPROVAL

Not needed; This study did not involve the use of animals or human participants.

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AUTHORS' CONTRIBUTIONS

Cesar Mendivil-Rangel: Conceptualization; Investigation; Writing – original draft.
Christian Lopez-Ayuso: Formal analysis; Visualization; Writing – review, editing.
Sarahi Garcia-Carvajal: Visualization.
Jose Martinez-Zepeda: Methodology.
Rogelio Scougall-Vilchis: Methodology.
Benjamín Aranda-Herrera: Formal analysis; Visualization.
Rene Garcia-Contreras: Methodology; Formal analysis; Visualization; Writing, review, editing.

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PEER REVIEW

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