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EVALUATION OF THE FORCE DEGRADATION OF NON-LATEX ORTHODONTIC ELASTICS AT DIFFERENT SALIVARY pH LEVELS

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Abstract

Background. Maintaining consistent orthodontic force is essential for efficient tooth movement; however, non-latex orthodontic elastics are susceptible to progressive force degradation under intraoral conditions. Salivary pH may affect the mechanical stability of polyurethane elastics, yet its influence across different immersion periods remains poorly understood. This study aimed to evaluate the force degradation of non-latex orthodontic elastics exposed to different salivary pH levels and immersion periods and to develop proposed clinical guidelines based on the findings.

Methods. An in vitro experimental study was conducted using fifty-four non-latex orthodontic elastics divided into nine experimental groups (n= 6 per group) according to three salivary pH conditions (5.0, 7.0, and 8.5) and three immersion periods (24 hours, 48 hours, and 1 week). The elastics were immersed in artificial saliva maintained at 37°C, and force degradation was measured using a calibrated digital force gauge. Data were analyzed using two-way analysis of variance (ANOVA) followed by Bonferroni post hoc test, with the level of significance set at $p < .05$.

Results. Force degradation increased significantly with longer immersion periods ($p < 0.001$), with the greatest force loss observed after one week. Salivary pH also significantly affected force degradation ($p <.001$), wherein acidic conditions produced the highest force loss, followed by alkaline conditions, while neutral pH demonstrated the lowest degradation. Mean force degradation was highest under acidic conditions at one week (57.95 ± 3.10 N), followed by alkaline conditions (50.42 ± 3.32 N) and neutral conditions (43.30 ± 3.19 N). No significant interaction was observed between salivary pH and immersion period (p = .167), indicating that both variables independently influenced force degradation.

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Conclusion. Salivary pH and immersion time significantly influenced the force degradation of non-latex orthodontic elastics under the conditions tested. Acidic conditions produced the greatest degradation, while neutral conditions produced the lowest, and degradation increased with prolonged immersion. The proposed guidelines emphasize consideration of salivary pH and duration of elastic use when monitoring non-latex orthodontic elastics. However, these preliminary guidelines require validation through dynamic and in vivo studies before specific clinical replacement protocols can be established.

Keywords*: Artificial saliva; force degradation; non-latex orthodontic elastics; orthodontic materials; polyurethane elastics; salivary pH*

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Research Highlights

What is the current knowledge?

- Orthodontic force degradation is an inherent property of elastomeric materials and may compromise treatment efficiency.
- Non-latex orthodontic elastics generally exhibit greater force degradation than latex elastics because of the viscoelastic behavior of polyurethane.
- Salivary pH and immersion time have been recognized as factors that influence the mechanical performance of orthodontic elastics.
- Most previous studies evaluated individual environmental factors rather than the combined effects of salivary pH and immersion period on non-latex orthodontic elastics.

What is new in this study?

- This study evaluated the independent effects of salivary pH and immersion time on the force degradation of non-latex orthodontic elastics under standardized in vitro conditions.
- Acidic conditions produced the greatest force degradation, whereas neutral pH demonstrated the lowest degradation.
- Immersion time significantly increased force degradation, with the greatest force loss observed after one week.
- The findings were translated into proposed clinical guidelines to support evidence-based replacement of non-latex orthodontic elastics.

INTRODUCTION

Orthodontic tooth movement depends on the application of light, continuous, and controlled forces that stimulate physiological remodeling of the periodontal ligament and surrounding alveolar bone (Castroflorio et al., 2022). Orthodontic elastics are widely used to generate these forces during the correction of malocclusions, particularly for interarch mechanics and occlusal adjustments. Among the available materials, non-latex orthodontic elastics have become an important alternative for patients with latex hypersensitivity because they eliminate the risk of allergic reactions while providing acceptable clinical performance (Alavi et al., 2014; Lacerda dos Santos et al., 2012). Their use has therefore increased in contemporary orthodontic practice as clinicians seek safer materials without compromising treatment outcomes.

Despite their clinical advantages, non-latex orthodontic elastics exhibit a major mechanical limitation: progressive force degradation after activation. Unlike ideal orthodontic materials that maintain relatively constant force over time, polyurethane-based non-latex elastics undergo stress relaxation and viscoelastic deformation, resulting in a gradual reduction in force delivery (Kamisetty et al., 2014; Ardani et al., 2018). This decline may occur rapidly during the first 24 to 48 hours and continues with prolonged intraoral exposure, potentially reducing the efficiency and predictability of orthodontic tooth movement. Consequently, frequent elastic replacement is often required to maintain adequate orthodontic forces throughout treatment (Ardani et al., 2018; Zheng et al., 2023).

Force degradation is influenced by several factors, including material composition, manufacturing process, stretching conditions, moisture absorption, temperature, and the chemical characteristics of saliva (Saccomanno et al., 2023; Selvaraj et al., 2023). Among these variables, salivary pH has attracted increasing attention because changes in oral acidity or alkalinity may alter the physicochemical stability of polyurethane elastics. Acidic conditions, which commonly occur following dietary acid exposure, bacterial metabolism, or reduced salivary buffering capacity, may accelerate hydrolytic degradation of polymer chains, leading to greater force loss than that observed under neutral conditions (Lacerda dos Santos et al., 2012; Xie et al., 2019). Likewise, prolonged exposure to the oral environment may further reduce the force-retention capacity of elastics through continuous stress relaxation and polymer deterioration.

Non-latex orthodontic elastics are primarily manufactured from polyurethane and are widely recommended for patients with latex allergy or hypersensitivity (Alavi et al., 2014; Lacerda dos Santos et al., 2012). Although they eliminate the allergenic proteins present in natural rubber latex, several laboratory investigations have demonstrated that they generally exhibit greater force degradation than conventional latex elastics because of their viscoelastic behavior and polymer composition (Alavi et al., 2014; Ardani et al., 2018). Consequently, clinicians frequently advise more frequent replacement of non-latex elastics to maintain effective orthodontic force throughout treatment (Saccomanno et al., 2023). However, evidence regarding the appropriate replacement interval under different salivary conditions remains limited, making clinical decision-making largely dependent on empirical judgment rather than standardized evidence.

Previous studies have investigated force degradation in orthodontic elastics under simulated oral conditions; however, most have focused on comparisons between latex and non-latex materials, evaluated only a single environmental factor, or examined limited immersion conditions. Although salivary pH and immersion time have individually been recognized as factors affecting the mechanical performance of orthodontic elastics, relatively few investigations have systematically evaluated their combined influence on the force degradation of non-latex orthodontic elastics using standardized experimental conditions. This knowledge gap limits the development of evidence-based recommendations regarding elastic replacement intervals and material selection, particularly for patients requiring non-latex alternatives during orthodontic treatment.

Addressing this gap is clinically important because maintaining consistent orthodontic force is essential for efficient tooth movement, treatment predictability, and patient compliance. Understanding how salivary pH and immersion time affect force degradation may assist orthodontists in optimizing replacement intervals, improving patient instructions, and selecting appropriate materials for different oral conditions. In addition, the findings may contribute to future improvements in the development of non-latex orthodontic materials with enhanced mechanical stability and greater resistance to environmental degradation.

Accordingly, this study evaluated the force degradation of non-latex orthodontic elastics exposed to different salivary pH levels over clinically relevant immersion periods under standardized in vitro conditions. Specifically, this study investigated the independent and combined effects of salivary pH and immersion time on force degradation and formulated proposed clinical guidelines based on the findings. Hence, the null hypothesis was that salivary pH, immersion time, and their interaction would not significantly affect the force degradation of non-latex orthodontic elastics under the experimental conditions.

LITERATURE REVIEW

Orthodontic elastics are essential components of fixed orthodontic treatment because they generate continuous forces required for tooth movement, interarch correction, and occlusal adjustment. The clinical effectiveness of these elastics depends on their ability to maintain adequate force throughout the prescribed period of use. However, elastomeric materials are inherently viscoelastic and gradually lose force after activation through stress relaxation, molecular rearrangement, and environmental degradation. This phenomenon, commonly referred to as force degradation or force decay, may reduce the efficiency of orthodontic treatment if elastics are not replaced at appropriate intervals. Previous investigations consistently reported that the greatest proportion of force loss occurs during the first 24 to 48 hours of clinical use, followed by a slower but continuous decline over time (Kamisetty et al., 2014; Ardani et al., 2018; Zheng et al., 2023). These findings emphasize the importance of understanding the variables that influence force degradation to optimize orthodontic treatment outcomes.

Non-latex orthodontic elastics were developed as an alternative for patients with latex hypersensitivity and are primarily manufactured from polyurethane-based polymers. Their introduction has improved the safety of orthodontic treatment by eliminating exposure to allergenic latex proteins while maintaining acceptable mechanical performance. Nevertheless, numerous laboratory investigations have demonstrated that non-latex elastics generally experience greater force degradation than conventional latex elastics because polyurethane exhibits more pronounced viscoelastic behavior and is more susceptible to environmental degradation. In addition, previous studies reported considerable variation among commercially available brands, indicating that polymer formulation and manufacturing processes substantially influence force-retention capacity.

Consequently, evidence-based recommendations regarding replacement intervals remain necessary to maximize the clinical performance of non-latex orthodontic elastics.

Salivary pH is considered an important environmental factor that may influence the mechanical behavior of orthodontic elastics. Variations in oral pH occur frequently because of dietary acid exposure, bacterial metabolism, systemic conditions, and individual differences in salivary buffering capacity. Acidic environments have been associated with accelerated hydrolytic degradation of polyurethane polymers, whereas alkaline conditions may also alter polymer stability through different degradation mechanisms.

These physicochemical changes reduce the ability of elastics to maintain stable tensile force during clinical use. Although several experimental studies have evaluated the influence of salivary pH on orthodontic elastics, the available evidence remains inconsistent because of differences in experimental protocols, immersion media, force measurement techniques, and observation periods. As a result, the magnitude of force degradation under different salivary pH conditions remains incompletely understood.

Existing literature has established that both salivary pH and exposure time influence the mechanical properties of orthodontic elastics. However, many previous investigations evaluated only individual variables, compared latex and non-latex materials, or examined limited experimental conditions. Few studies have systematically investigated the combined effects of clinically relevant salivary pH levels and immersion periods on the force degradation of polyurethane-based non-latex orthodontic elastics under standardized laboratory conditions. Furthermore, limited evidence is available to translate laboratory findings into practical recommendations for routine clinical use. Addressing this gap, the present study evaluated the independent and combined effects of salivary pH and immersion time on the force degradation of non-latex orthodontic elastics and developed proposed clinical guidelines to support evidence-based orthodontic practice.

METHODOLOGY

Design

This study employed an in vitro experimental research design to evaluate the force degradation of non-latex orthodontic elastics under different salivary pH levels and immersion periods. A total of 54 non-latex orthodontic elastics were allocated into nine experimental groups, representing the combination of three salivary pH conditions (pH 5.0, 7.0, and 8.5) and three immersion periods (24 hours, 48 hours, and 1 week), with six specimens assigned to each group. This design enabled the evaluation of the independent and combined effects of salivary pH and immersion time on the force degradation of non-latex orthodontic elastics under standardized laboratory conditions.

Environment

The study was conducted in Cebu, Philippines. Preparation of the acrylic experimental jigs was performed at the Orthodontic Simulation Room, Cebu Doctors' University, Mandaue City. Preparation of artificial saliva solutions, sample incubation, and force measurements were conducted at F.A.S.T. Laboratories, Mandaue City, Cebu. All experimental procedures were performed under standardized laboratory conditions. Artificial saliva was maintained at 37°C throughout the immersion period to simulate the intraoral environment.

Participants

The study included 54 non-latex orthodontic elastics (¼ inch, 4.5 oz, medium force) obtained from the same manufacturer and production lot to minimize material variability. The elastics were visually inspected for obvious defects and then randomly allocated into nine experimental groups using a computer-based randomization procedure via the RAND() function in Microsoft Excel. Each experimental group consisted of six elastics representing the combinations of three salivary pH levels (5.0, 7.0, and 8.5) and three immersion periods (24 hours, 48 hours, and 1 week).

Instruments

The primary instruments used in this study included a calibrated digital force gauge with an accuracy of ±0.01 N for measuring elastic force, a digital pH meter for verification of artificial saliva pH levels, a thermostatically controlled laboratory incubator maintained at 37°C, and customized acrylic jigs to standardize elastic extension during immersion. Commercial Fusayama–Meyer artificial saliva was used as the immersion medium and adjusted to the required pH levels using 0.1 M hydrochloric acid (HCl) and 0.1 M sodium hydroxide (NaOH).

Data Collection Procedure

Artificial saliva solutions were prepared and adjusted to pH 5.0, 7.0, and 8.5 using calibrated laboratory equipment. Each elastic was mounted on a standardized acrylic jig at a standardized extension distance of 20 mm, which was used to simulate the approximate clinical interarch distance encountered during orthodontic elastic wear and to ensure uniform elastic elongation and minimize measurement variability. Force measurements were obtained before immersion and after each designated immersion period (24 hours, 48 hours, and 1 week) using a calibrated digital force gauge. Force degradation was calculated by comparing the initial and final force values for each specimen.

Data Analysis

Descriptive statistics, including mean and standard deviation, were calculated for each experimental group. Two-way analysis of variance (ANOVA) was performed to evaluate the effects of salivary pH level and immersion time, as well as their interaction, on force degradation. Partial eta squared (ηp^2) was reported as a measure of effect size for the main effects and interaction. When statistically significant differences were identified, Bonferroni post hoc tests were conducted for pairwise comparisons. Statistical significance was established at $p < .05$, and all analyses were performed using IBM SPSS Statistics.

Ethical Considerations

As an in vitro laboratory investigation, this study did not involve human participants or animals and therefore did not require informed consent. Nevertheless, approval to conduct the study was obtained from the appropriate institutional authorities. All laboratory procedures were performed in accordance with institutional safety protocols, and experimental materials and chemical waste were handled and disposed of following the standard operating procedures of F.A.S.T. Laboratories.

RESULTS

The rate of force degradation of non-latex orthodontic elastics was evaluated according to salivary pH conditions and immersion time intervals. Descriptive statistics are presented first, followed by inferential analysis using two-way analysis of variance (ANOVA) and Bonferroni post hoc comparisons.

The force degradation of non-latex orthodontic elastics according to salivary pH condition and immersion period is shown in Table 1. Across all salivary pH conditions, force degradation increased progressively with longer immersion periods. The highest mean force degradation was observed under acidic conditions (pH 5.0) after 1 week (57.95 ± 3.10 N), whereas the lowest mean value was recorded under neutral conditions (pH 7.0) after 24 hours (25.87 ± 3.59 N). At each immersion period, the acidic pH group demonstrated the highest mean force degradation, followed by the alkaline group, while the neutral group consistently exhibited the lowest mean values.

Table 1.

Mean Force Degradation (N) of Non-Latex Orthodontic Elastics According to Salivary pH Condition and Immersion Periods

		Time Period		
pH Condition	*n*	24 hours	48 hours	1 week
Acidic (pH 5.0)	6	34.53±2.25	45.47±3.11	57.95±3.10
Neutral (pH 7.0)	6	25.87±3.59	35.48±2.64	43.30±3.19
Alkaline (pH 8.5)	6	30.18±3.32	39.88±1.73	50.42±3.32

Note. *Values are presented as mean ± standard deviation (SD).*

The two-way analysis of variance (ANOVA) for the rate of force degradation of non-latex orthodontic elastics according to salivary pH condition and immersion period is shown in Table 2. There was no significant interaction between salivary pH condition and immersion period, $F(4, 45) = 1.700$, $p = .167$, $\eta p^2 = .131$, indicating that the effect of immersion period did not significantly differ across the pH conditions. However, significant main effects were observed for salivary pH, $F(2, 45) = 62.880$, $p < .001$, $\eta p^2 = .736$, and immersion period, $F(2, 45) = 211.413$, $p < .001$, $\eta p^2 = .904$.

Table 2.

Two-Way Analysis of Variance for Force Degradation of Non-Latex Orthodontic Elastics

Source	Type III Sum of squares	df	Mean Square	F-value	*p*-value	Partial Eta Squared
pH	1,109.779	2	554.890	62.880	.000	.736
Time	3,731.287	2	1,865.644	211.413	.000	.904
pH * Time	59.997	4	14.999	1.700	.167	.131
Error	397.108	45	8.825			
Total	5,298.172	53				

Table 3 presents the Bonferroni post hoc comparisons among the three salivary pH conditions. Significant differences in mean force degradation were observed across all pairwise comparisons ($p < .001$). The acidic group showed a significantly greater mean force degradation than the neutral group (mean difference = 11.10, 95% CI [8.64, 13.56]) and the alkaline group (mean difference = 5.82, 95% CI [3.36, 8.29]). The alkaline group also showed a significantly greater mean force degradation than the neutral group (mean difference = 5.28, 95% CI [2.82, 7.74]).

Table 3.

Bonferroni Post Hoc Comparison of Mean Force Degradation According to Salivary pH Condition

pH Conditions	Mean Difference	*p*-value	95% CI of the Mean Difference	
			Lower Bound	Upper Bound
Acidic (pH 5.0) vs Neutral (pH 7.0)	11.10	<.001	8.64	13.56
Acidic (pH 5.0) vs Alkaline (pH 8.5)	5.82	<.001	3.36	8.29
Neutral (pH 7.0) vs Alkaline (pH 8.5)	5.28	<.001	2.82	7.74

In addition, Table 4 presents the Bonferroni post hoc comparisons among the three immersion periods. Significant differences in mean force degradation were observed across all pairwise comparisons ($p < .001$). Mean force degradation was significantly higher at 48 hours than at 24 hours (mean difference = 10.08, 95% CI [7.62, 12.55]), significantly higher at 1 week than at 24 hours (mean difference = 20.36, 95% CI [17.90, 22.82]), and significantly higher at 1 week than at 48 hours (mean difference = 10.28, 95% CI [7.82, 12.74]).

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Table 4.

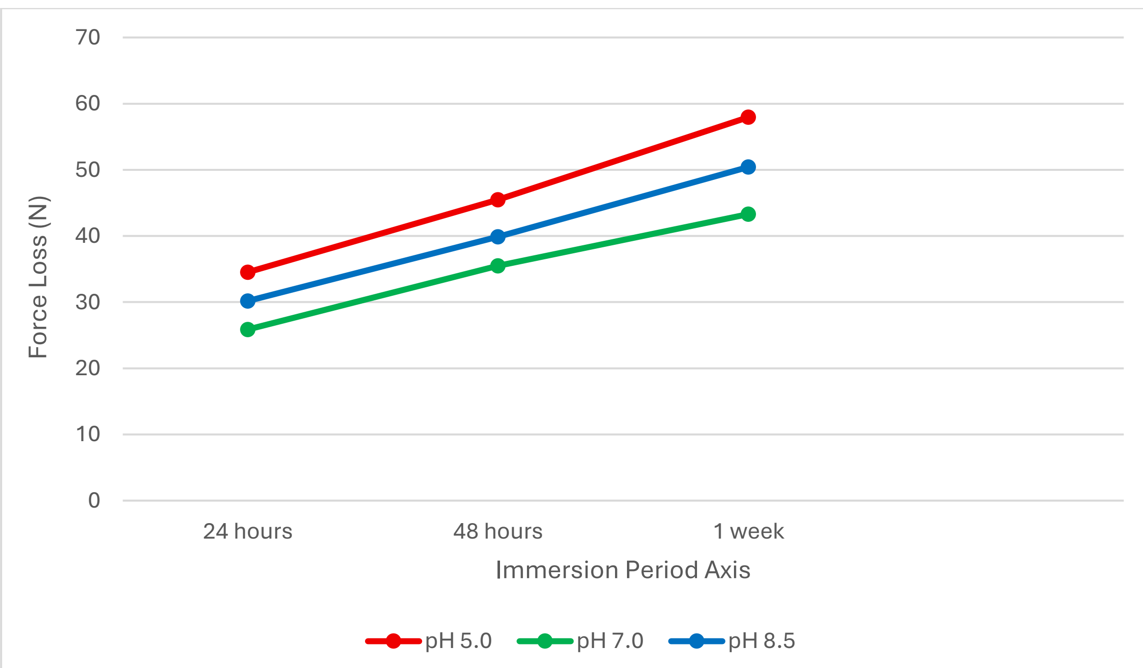
Bonferroni Post-Hoc Test for the Rate of Force Degradation (N) among the Time Periods

Time Periods	Mean Difference	*p*-value	95% CI of the Mean Difference	
			Lower Bound	Upper Bound
24 hours vs 48 hours	10.08	<.001	7.62	12.55
24 hours vs 1 week	20.36	<.001	17.90	22.82
48 hours vs 1 week	10.28	<.001	7.82	12.74

Figure 1 illustrates the mean force degradation trajectories across the three immersion periods (24 hours, 48 hours, and 1 week) under acidic (pH 5.0), neutral (pH 7.0), and alkaline (pH 8.5) conditions.

Figure 1.

Mean Force Degradation of Non-Latex Orthodontic Elastics Across Immersion Periods Under Different Salivary pH Conditions



The pattern of force degradation across the three salivary pH conditions throughout the immersion periods as shown in Figure 1. All experimental groups demonstrated a progressive increase in force degradation over time. The acidic group consistently exhibited the highest force degradation, whereas the neutral group maintained the lowest values. The alkaline group showed intermediate values across all observation periods.

DISCUSSION

The present study evaluated the effect of different salivary pH conditions and immersion periods on the force degradation of polyurethane-based non-latex orthodontic elastics. The findings demonstrated that both salivary pH and immersion time significantly influenced force degradation. Elastics immersed in acidic artificial saliva (pH 5.0) exhibited the greatest force degradation, whereas those stored under neutral conditions (pH 7.0) consistently maintained the highest force-retention capacity. The alkaline group (pH 8.5) demonstrated intermediate force degradation values, suggesting that deviations from physiologic pH in either direction may adversely affect the stability of polyurethane elastics.

Likewise, force degradation progressively increased with longer immersion periods, with the greatest reduction observed after one week. Although both salivary pH and immersion time independently affected force degradation, no significant interaction was identified between these variables, indicating that each factor contributed separately to the deterioration of the elastics.

These findings are consistent with previous investigations reporting that non-latex orthodontic elastics undergo progressive force decay during clinical use because of the viscoelastic characteristics of polyurethane and its susceptibility to hydrolytic degradation. Previous studies by Kamisetty et al. (2014), Kumari et al. (2025), and Virdi et al. (2024) similarly demonstrated that acidic environments and prolonged exposure accelerate deterioration of polyurethane elastics through polymer chain degradation and stress relaxation. The greater force degradation observed under acidic conditions may be explained by acid-catalyzed hydrolytic degradation within susceptible polyurethane polymer linkages. Increased hydrogen ion activity under acidic conditions may facilitate hydrolytic cleavage of susceptible ester and urethane bonds within the polymer chains, disrupting intermolecular interactions and reducing the material's ability to recover its original elastic properties after stretching. Conversely, neutral pH provides a relatively stable environment that may minimize chemical degradation and better preserve the mechanical integrity of polyurethane elastics.

From a clinical perspective, these findings emphasize that the oral environment should be considered when prescribing non-latex orthodontic elastics, particularly for patients with latex hypersensitivity. Individuals who frequently consume acidic foods or beverages or present with persistently acidic salivary conditions may experience faster degradation of elastic force, potentially reducing treatment efficiency if replacement intervals are prolonged. The observed progressive force loss also supports the importance of regular elastic replacement to maintain consistent orthodontic force delivery throughout treatment.

The present study has several strengths. A standardized in vitro design was employed using controlled salivary pH levels, constant incubation temperature, uniform immersion periods, and elastics from the same manufacturer and production batch, thereby minimizing experimental variability.

Nevertheless, several limitations should be acknowledged. Because the investigation was conducted under static laboratory conditions, the findings may not completely replicate the complex intraoral environment, where cyclic masticatory loading, temperature fluctuations, salivary enzymes, plaque biofilm, microbial activity, and patient-related factors may further influence elastic degradation. The use of artificial saliva also does not fully reproduce the composition and biological variability of natural saliva. In addition, the static immersion design did not simulate the repeated stretching and relaxation cycles that occur during mastication and clinical function. Furthermore, only one brand, size, and force level of non-latex elastic was evaluated, which may limit the generalizability of the findings to other commercially available products. Therefore, future studies should incorporate dynamic loading, thermal cycling, natural saliva or more biologically representative media, and in vivo clinical evaluation to determine whether the observed degradation patterns are consistent under actual oral conditions.

Overall, this study provides additional evidence regarding the degradation behavior of polyurethane-based non-latex orthodontic elastics under different salivary pH conditions and immersion periods. The findings indicate that salivary pH and duration of exposure are important factors associated with force degradation, while their nonsignificant interaction suggests that these factors exerted independent effects under the conditions tested. These findings provide a basis for considering the oral environment and duration of elastic use when planning clinical management, while recognizing that the present in vitro findings require clinical validation before specific replacement protocols can be established.

PROPOSED GUIDELINES

Based on the findings of the present in vitro study, the following preliminary guidelines are proposed for the clinical use of non-latex orthodontic elastics: (1) clinicians should consider salivary pH as a potential factor influencing the force degradation of polyurethane-based non-latex elastics; (2) prolonged intraoral use should be considered when assessing the expected force delivery of elastics, as force degradation increased with longer immersion periods in the present study; (3) regular replacement of non-latex elastics should be maintained as part of routine orthodontic management to support consistent force delivery; and (4) patients with conditions that may be associated with persistently acidic oral environments may require closer monitoring of elastic performance. These recommendations are preliminary and should not be interpreted as a substitute for established clinical protocols, as the present findings were obtained under controlled in vitro conditions and require confirmation through dynamic and in vivo studies.

CONCLUSION

Based on the findings of the present study, non-latex orthodontic elastics exhibited progressive force degradation with increasing immersion time, with the greatest degradation observed after one week. Salivary pH also significantly influenced force degradation, with acidic conditions producing the highest degradation and neutral conditions producing the lowest. Both salivary pH and immersion time exerted significant independent effects, while their interaction was not statistically significant. These findings suggest that environmental pH and duration of exposure are important considerations in the performance of polyurethane-based non-latex orthodontic elastics. However, because the study was conducted under controlled in vitro conditions, the findings should be clinically validated before specific replacement intervals are established.

RECOMMENDATIONS

Practice. Clinicians should consider salivary pH and duration of elastic use when monitoring the performance of non-latex orthodontic elastics. Patients who may have persistently acidic oral conditions should receive appropriate monitoring and reinforcement of routine elastic replacement.

Policy. Dental practices may incorporate guidance on proper elastic replacement and patient instructions regarding factors that may affect elastic performance into routine orthodontic protocols.

Theory. The findings support further investigation of the relationship between environmental pH, immersion duration, and the degradation behavior of polyurethane-based orthodontic elastics.

Education and Training. Orthodontic education and clinical training should emphasize the effects of oral environmental conditions and prolonged elastic use on force delivery, including appropriate patient counseling regarding elastic replacement.

Future Research Directions. Future studies should evaluate different brands, elastic sizes, and force levels using dynamic cyclic loading, thermal cycling, natural saliva or more biologically representative media, salivary enzymes, and plaque biofilm conditions. In vivo clinical studies are also recommended to determine whether the degradation patterns observed under laboratory conditions are reproduced in actual oral environments.

List of Abbreviations

ANOVA – Analysis of Variance
CI – Confidence Interval
HCl – Hydrochloric Acid
NaOH – Sodium Hydroxide
N – Newton
pH – Potential of Hydrogen
SD – Standard Deviation

Declarations

Ethical approval and consent to participate

Not applicable. This in vitro experimental study did not involve human participants, animals, or identifiable human data; therefore, ethical approval and informed consent were not required.

Consent for publication
Not applicable. No individual participant data are reported.

Availability of data and materials
The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

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Declaration of Generative AI and AI-assisted Technologies
The authors used ChatGPT (OpenAI) and Grammarly AI solely for language editing and readability enhancement. All scientific content, analyses, interpretations, and conclusions were developed, reviewed, and approved by the authors, who take full responsibility for the content of this manuscript.

Competing Interests
The authors declare no competing interests.

Author's contributions
M.G.A. conceptualized the study, developed the methodology, performed the formal analysis, prepared the original draft, created the visualizations, and managed the project.

A.L.F.L. contributed to the conceptualization and methodology, supervised the study, critically reviewed and edited the manuscript. Both authors read and approved the final version of the manuscript.

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