Sliding Mechanics Involving a Twin Guiding Arch System
An Experimental Pilot Study

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- Endowed Chair for Oral Technology -

To my parents, for their unwavering support.

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List of Abbreviations

Abbreviation	Full Term and Description	Unit
1Br	Single-wire configuration	-
2Br	Dual-wire configuration	-
ANOVA	Analysis of Variance	-
CR	Center of Resistance	-
DFd	Degrees of Freedom (denominator)	-
DFn	Degrees of Freedom (numerator)	-
F	Force	N (Newton)
ISO	International Organization for Standardization	-
M	Moment (Torque)	Nmm (Newton-millimeter)
M/F ratio	Moment-to-Force Ratio	Nmm/N
OMSS	Orthodontic Measurement and Simulation System	-
P-value	Probability value	-
R	Retraction Distance	mm (millimeter)
R squared	Coefficient of Determination	-
R/F ratio	Retraction-per-Force Ratio	mm/N
T/R ratio	Torque-per-Retraction Ratio	Nmm/mm

1. Introduction

Dental protrusion is characterized by the dentoalveolar flaring of the maxillary or both maxillary and mandibular anterior teeth (Hogeman et al., 1967). This condition is of considerable clinical relevance in dentistry, particularly within the field of orthodontics. Incidence rates for maxillary protrusion vary widely, ranging from 5 % to 20 %, and it is observed across different ethnic groups, though it is more commonly seen in African-American and Asian populations (Al-Rokhami et al., 2022; Chen et al., 2021; Guo et al., 2023; Hong et al., 2019). The etiology of dental protrusion is multifactorial, encompassing genetic factors as well as environmental influences such as mouth breathing, tongue habits, and lip habits (Hiltz, 2007; Nishio et al., 2016; Shinkai et al., 2023; Townsend et al., 2012).

Maxillary anterior tooth protrusion significantly affects facial aesthetics by increasing facial convexity and causing upper lip projection, which is often considered unappealing. Consequently, patients frequently seek orthodontic treatment to enhance their facial appearance, thereby improving their self-esteem and overall quality of life (de Couto Nascimento et al., 2016; Jiang et al., 2021; Johal et al., 2014; Yu et al., 2023; Zhang et al., 2023). The primary treatment goal in these cases is to reduce maxillary dentoalveolar protrusion, leading to a more balanced and aesthetically pleasing facial profile. The typical treatment plan for reducing maxillary dentoalveolar protrusion involves the extraction of bilateral maxillary premolars followed by the retraction of the anterior teeth (Miglani et al., 2013; Ordóñez et al., 2018; Vasoglou et al., 2023; Yu et al., 2023). This approach aims to maximize the retraction of anterior teeth while minimizing any unwanted mesial movement of the maxillary molars. Successful treatment often results in a favorable soft-tissue response, reducing lip eversion and protrusion, and achieving a more harmonious facial appearance (Fig. 1).

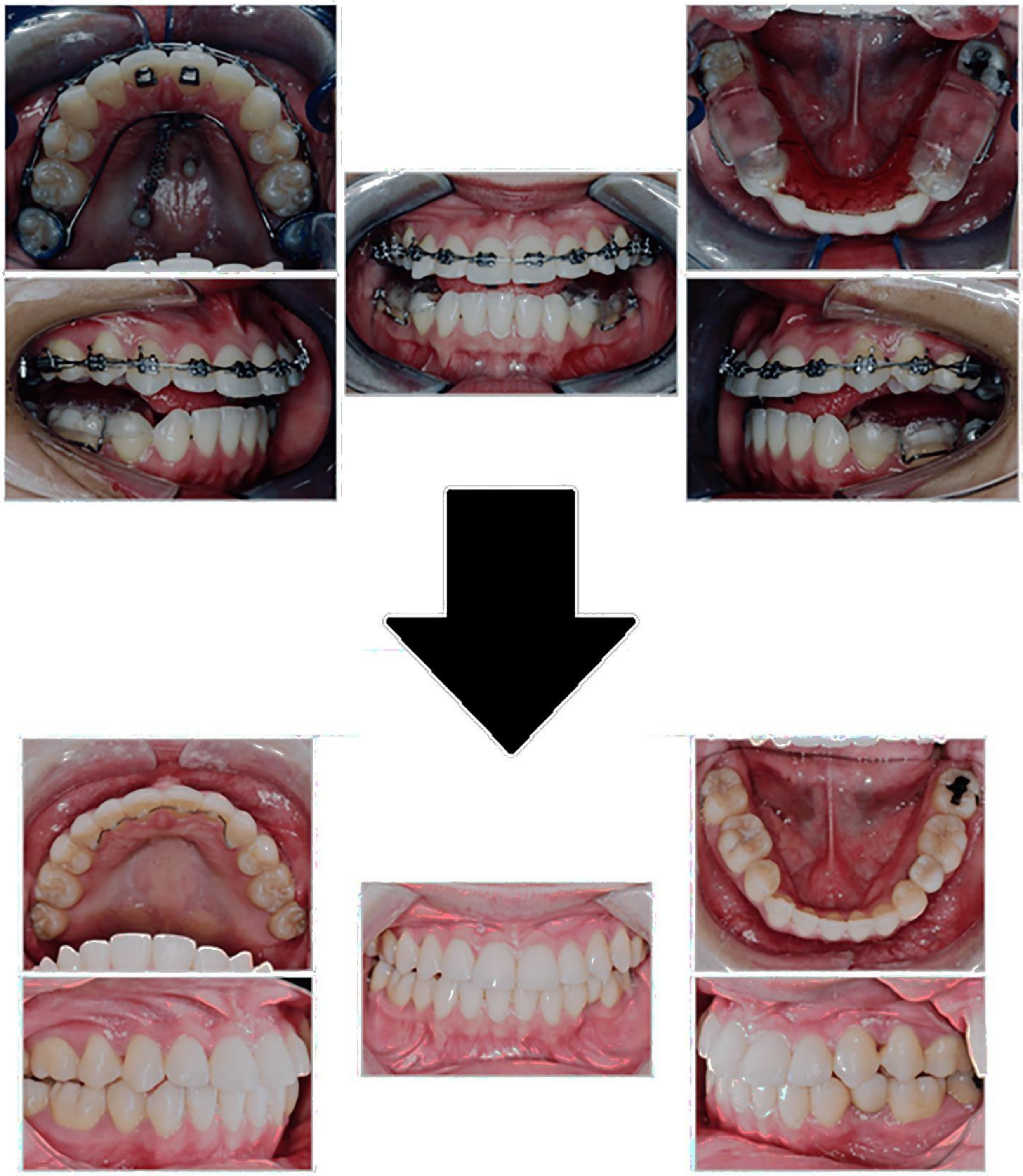

Figure 1: Maxillary anterior tooth protrusion impacts facial aesthetics by increasing facial convexity and upper lip projection, often seen as unappealing. Patients seek orthodontic treatment to improve their appearance and self-esteem. The primary goal is to reduce maxillary dentoalveolar protrusion for a balanced facial profile, typically involving the extraction of maxillary premolars and retraction of anterior teeth. This treatment aims to enhance facial harmony by reducing lip eversion and protrusion.

Orthodontic anchorage is essential for preventing unwanted tooth movements during treatment. Anchorage refers to the resistance to the reactive forces generated during tooth movement. Failure to maintain the position of the anchorage units can lead to “anchorage loss,” compromising the effectiveness of anterior retraction (Geron et al., 2003; Xu, 2017). Various methods are employed to achieve maximum anchorage, including the use of intraoral appliances like transpalatal arches or Nance holding arches, and extraoral appliances like headgear (Geron et al., 2003; Xu, 2017). Skeletal anchorage using dental implants, screws, and miniplates also plays a significant role in providing stable anchorage (Alexandre et al., 2019; Mheissen et al., 2023; Sugawara, 2014; Sugawara et al., 2005). Controlling the torque of the incisors is crucial during maximum anterior retraction (Tepedino et al., 2023). The moment/force ratio (M/F ratio) is a key determinant in managing incisor torque (Cattaneo et al., 2008). The labiolingual inclination and anteroposterior position of the maxillary incisors significantly influence the esthetics of the smiling profile (Choi et al., 2022; Jiang et al., 2021). Effective torque control ensures that the maxillary incisors are positioned optimally, contributing to an improved facial appearance (Choi et al., 2022; Jiang et al., 2021).

Among the techniques for closing extraction spaces, sliding mechanics and loop mechanics are the most commonly used. Sliding mechanics is often preferred due to its simplicity, ease of reactivation, and patient comfort (Prashar et al., 2021; Renji et al., 2021; Ribeiro et al., 2016; Sebastian et al., 2021; Singh et al., 2024). However, various mechanical properties such as archwire stiffness, friction, and bracket-wire play influence the resultant tooth movement, presenting challenges in achieving the desired outcomes (Renji et al., 2021; Sebastian et al., 2021; Singh et al., 2024). Friction is an inherent aspect of fixed orthodontic appliances and plays a significant role in tooth movement (Renji et al., 2021; Shah et al., 2019). It impedes displacement during canine retraction along a continuous arch wire into the site of a first-premolar extraction and affects anterior retraction processes when the arch wire slides through posterior brackets and buccal tubes. Understanding and managing friction is crucial for optimizing treatment efficiency (Montiel et al., 2024; Renji et al., 2021; Shah et al., 2019).

The aim of this *in vitro* study was to perform a comprehensive biomechanical evaluation of a twin guiding arch system as an alternative technique for maxillary anterior teeth retraction. An experimental study was performed to precisely measure the effectiveness of various wire and bracket combinations. This approach uses resin models within a sophisticated simulation system to isolate and quantify key mechanical variables such as forces, moments (torque), and the resultant tooth segment displacement. Through this focused experimental approach, the study seeks to generate foundational data on force systems and retraction efficiency, thereby providing a scientific basis for potential future clinical applications and protocols.

1.1 Literature Review

Maxillary anterior tooth retraction is a cornerstone of orthodontic treatment, essential for creating space and correcting dental crowding. This process involves moving the upper front teeth backward and requires precise control over the mechanics to achieve optimal results. Various techniques and materials have been developed to enhance the effectiveness and efficiency of this retraction process. Sliding mechanics are one of the most widely used methods for maxillary anterior teeth retraction (Table 1). This technique employs continuous archwires that slide through brackets and buccal tubes to move the teeth. The simplicity of sliding mechanics, along with its ease of implementation, makes it a popular choice among orthodontists. Additionally, the ability to easily reactivate the archwires during the treatment process adds to its appeal. Patients also generally find sliding mechanics comfortable, which improves compliance and treatment outcomes.

However, friction between the archwire and bracket slot can impede tooth movement, posing a significant limitation. The mechanical properties of the archwire, including stiffness and bracket-wire play, also influence the success of this technique (Kuc et al., 2022). For example, in a meta-analysis, different force delivery systems for orthodontic space closure using sliding mechanics were compared. Thirteen randomized controlled trials, including both parallel-arm and split-mouth designs, were included in the study, involving orthodontic patients treated with fixed appliances. It was found that nickel titanium (NiTi) closed coil springs were significantly more effective than elastomeric power chains and active ligatures in terms of the rate of tooth movement. The network meta-analysis further confirmed that NiTi coil springs were the best method for space closure, with a 99 % chance of being the most effective. However, the need for standardization in study design and the development of core outcome sets could be important in future research (Sebastian et al., 2022).

In another study by Barlow and Kula the efficiency of sliding mechanics in closing extraction spaces in orthodontics was examined. Various factors influencing the rate of tooth movement were analyzed through ten prospective clinical trials. It was found that nickeltitanium coil springs produce a more consistent force and faster rate of closure compared to active ligatures, although elastomeric chains showed similar rates of closure. It was highlighted the need for more clinical research to validate these findings and suggested that while nickel titanium springs are effective, their cost may not justify their use over less expensive alternatives like elastomeric chains. The understanding of the mechanics and the influence of different materials and methods on space closure are important for making informed clinical decisions (Barlow et al., 2008). Maxillary anterior tooth retraction is a fundamental aspect of orthodontic treatment, crucial for addressing dental crowding and creating space. Sliding mechanics, which utilize continuous archwires sliding through brackets and buccal tubes, are widely favored due to their simplicity, ease of implementation, and patient comfort. Despite these advantages, friction between the archwire and bracket slot can hinder tooth movement, and the mechanical properties of the archwire play a significant role in the technique’s success. The characteristics of maxillary anterior retraction are summed up in table 1.

Table 1: Characteristics of Sliding Mechanics for Maxillary Anterior Tooth Retraction

Aspect	Details
Technique	Sliding mechanics for maxillary anterior tooth retraction
Method	Uses continuous archwires sliding through brackets and buccal tubes
Popularity	Favored for its simplicity and ease of implementation
Reactivation	Archwires can be easily reactivated or changed during treatment
Patient Comfort	Generally comfortable, leading to better compliance and outcomes
Limitation	Friction between archwire and bracket slot can impede movement
Influencing Factors	Mechanical properties of archwire, stiffness, and bracket-wire play

Loop mechanics provide an alternative approach with its own set of advantages. Different loop configurations can be customized to suit specific orthodontic cases, offering predictability and versatility in tooth movement. Loops can be designed to achieve precise control over the retraction process, making them reliable for achieving the desired outcomes. However, the complexity of some loop designs requires precise adjustments, which can be time-consuming and challenging. Moreover, patient cooperation is crucial for the success of loop mechanics, as compliance with the treatment protocol is essential (Chakravarthy et al., 2014; Prashar et al., 2021; Zhao et al., 2020). For example, a study aimed to evaluate the force, moment, and moment/force (M/F) ratio generated by activating four different loops made of titanium molybdenum alloy (TMA) wire: T loop, Kalra Simultaneous Intrusion and Retraction (KSIR) loop, Omega loop, and Teardrop loop. Finite element method (FEM) models of these loops were created, and different preactivation bends were applied. The loops were then activated and analyzed using ANSYS software. It was found that, without preactivation bends, the Omega loop generated the highest force, while the T loop produced the least force. With preactivation bends, the Teardrop loop exhibited the highest force, and the T loop again showed the least force. The T loop with preactivation bends demonstrated the most favorable properties for frictionless mechanics in space closure, making it comparatively reliable for clinical use (Haris et al., 2018). Therefore, loop mechanics are essential in orthodontics due to their ability to provide precise control over tooth movement, making them a reliable and versatile option for achieving desired treatment outcomes. Characteristics of loop mechanics are listed in Table 2.

Table 2: Characteristics of Loop Mechanics for Closing Extraction Spaces

Aspect	Details
Key Techniques	**Begg Technique:** Uses light forces for tooth movement and root control. **T-Loop:** Provides controlled movement with minimal unwanted tipping.
Anchorage	**Micro-implants:** Provide stable anchorage, preventing unwanted movement of posterior teeth.
Force Application	**Nickel Titanium (NiTi) Springs:** Commonly used for consistent force delivery (approx. 1.5–2.0 N). **Stainless Steel (SS) Wires:** Valued for their stiffness and control.
Clinical Applications	**Segmented Arch Technique:** Often combined with implants for effective and precise space closure.
Biomechanicals	**Moment-to-Force (M/F) Ratio:** Critical for controlling the type of tooth movement (e.g., bodily vs. tipping). **Activation Range:** Loops generally offer a greater activation range, providing a more constant force over time.

The selection of archwire and bracket systems plays a crucial role in the effectiveness of maxillary anterior teeth retraction. Different combinations of wires and brackets can impact the friction, stiffness, and overall mechanics of tooth movement (Kuc et al., 2022; Kuc et al., 2024). As an example, Robert P. Kusy focused on the influence of force systems on archwire-bracket combinations in orthodontics. Simplified free-body diagrams and equilibrium principles are used to present orthodontic forces and couples in three principal directions: labial-lingual, mesial-distal, and occlusal-gingival. These diagrams illustrate the forces and couples applied to a single tooth or a group of teeth, excluding frictional effects from appliances. By applying equilibrium principles, it is shown that these forces and couples are resisted by each root in an equal but opposite manner. In this study, the concept of an equivalent force system at the center of resistance was introduced, simplifying the understanding of tooth mechanics. Various examples, such as labial or lingual displacement, intrusion or extrusion, and bodily translation or rotation, are provided to demonstrate this approach, showing the impact of friction and the role of different orthodontic appliances in these force systems (Kusy, 2005).

Another study’s findings indicate that the effectiveness of maxillary anterior teeth retraction is significantly impacted by the selection of archwire and bracket systems. It was found that more friction is generated by titanium brackets compared to stainless steel brackets, which affects the force needed for tooth movement. Additionally, more friction is produced by narrow brackets than by wider brackets, influencing the efficiency of retraction. Larger wire dimensions were observed to increase friction, requiring greater force for effective tooth movement. Furthermore, elastomeric modules were found to create more friction than stainless steel ligature wires, impacting the overall retraction process. It was also noted that wet conditions increase friction compared to dry conditions, affecting the applied forces. These factors underscore the importance of careful selection of archwire and bracket combinations to optimize the retraction of maxillary anterior teeth, ensuring effective and efficient orthodontic treatment (Husain, 2011).

Therefore, the selection of archwire and bracket systems significantly influences the effectiveness of maxillary anterior teeth retraction. Factors such as friction, bracket width, wire dimensions, and material type play crucial roles in optimizing orthodontic treatment outcomes. Advances in materials and design have aimed to minimize friction while maintaining control over tooth positioning. Research has shown that various wire/bracket combinations can significantly influence the efficiency of the retraction process. Manufacturers have developed archwires and brackets with reduced friction properties, enhancing the overall effectiveness of orthodontic treatment (Dobai et al., 2022; Kuc et al., 2022; Kuc et al., 2024).

Orthodontic treatment methods for maxillary anterior teeth retraction include traditional fixed braces, clear aligners, and other advanced techniques (Balachandran et al., 2019; Bonnick et al., 2011; Kankam et al., 2019; Meng et al., 2023; Robertson et al., 2020; Tang et al., 1990; Xia et al., 2024). Traditional fixed braces, which use metal or ceramic brackets with archwires, are commonly used due to their effectiveness and control over tooth movement. Clear aligners offer a discreet alternative, providing aesthetic benefits and patient comfort. Retainers are often used after active treatment to maintain tooth position and ensure long-term stability of the achieved results. An individualized approach to treatment is crucial, as it allows for customization based on the specific needs of each patient.

Despite advancements in techniques and materials, challenges such as friction remain a significant obstacle during anterior teeth retraction. The customization of treatment to suit individual patient needs requires ongoing research to optimize outcomes. Addressing these limitations through continued innovation and research is essential for enhancing the efficacy of orthodontic treatment. This study was designed to develop a feasible and effective treatment technique for maxillary anterior teeth retraction. It consisted of an in vitro experimental phase to measure the effectiveness of different wire/bracket combinations in anterior retraction. The experimental phase involved the use of resin models to simulate the orthodontic environment, allow-ing for precise measurements of variables such as primary force, path of tooth move-ment, and torque angle. Additionally, an orthodontic measurement and simulation sys-tem was employed to assess the impact of wire stiffness, friction, and bracket-wire play on tooth movement. This experimental approach aimed to establish the biomechanical efficacy of various wire/bracket combinations. Statistical comparisons were made between different groups of wire/bracket combinations, including single and double wires in brackets, as well as a control simulation group. The primary focus was on the effectiveness of a twin arch system in achieving the desired tooth movement and restoring the maxillary anterior teeth. Therefore, this study provides a comprehensive analysis of different wire/bracket combinations, emphasizing the potential benefits of the twin arch system. By integrating experimental and clinical data, the study offers valuable insights into optimizing orthodontic treatment techniques for maxillary anterior teeth retraction, ultimately aiming to enhance patient outcomes and treatment efficacy.

1.2 Aims and Hypotheses

The primary aim of this study was to evaluate the efficacy of a twin guiding arch system in optimizing maxillary anterior teeth retraction. Specific objectives of this *in vitro* investigation included:

1. Investigating the biomechanical properties (forces and moments) generated by different wire/bracket combinations in terms of torque generation and frictional resistance during simulated retraction.
2. Comparing the performance of various configurations, including single and dual archwires, in achieving efficient retraction and controlled tooth segment movement.
3. Providing a detailed, foundational biomechanical analysis to inform potential clinical strategies and serve as a basis for future research.

The hypotheses proposed are that the twin guiding arch system enhances anteri-or tooth retraction efficiency compared to conventional single-arch systems, and that dual-wire configurations provide better torque control than single-wire configurations.

2. Materials and methods

2.1 Materials

A self-ligating bracket system with a 0.022″ slot size (BioQuick®, Forestadent®, Pforzheim, Germany) was used for this study. This system was chosen due to its capability to accommodate a second wire in an auxiliary slot. Stainless steel wires (Remanium®, Dentaurum, Pforzheim, Germany) in the following dimensions were utilized: 0.012″, 0.014″, 0.016″, 0.018″, 0.017×0.025″, and 0.019×0.025″. The dimensions and de-scriptors of the brackets and wires are detailed in Table 3. Molar tubes (Titanium Buccal Tubes, Ormco BV, Amersfoort, The Netherlands) were also used, along with orthodontic elastic chains (Generation II (closed space) Power Chain grey, Ormco BV, Amersfoort, The Netherlands) as force-delivering elements.

The experimental setup was designed to replicate the materials that would be used in a potential clinical setting, ensuring the relevance of the biomechanical findings.

Table 3: Dimensions and Descriptors of Brackets and Wires Used in the Study

Component	Details	Dimensions (Millimeters)	Descriptor*
Bracket	Main Slot Height	0.56	22
	Auxiliary Slot	0.40 × 0.40	16×16
Wires	Stainless Steel (Round)	0.30 (Ø)	12
	Stainless Steel (Round)	0.35 (Ø)	14
	Stainless Steel (Round)	0.40 (Ø)	16
	Stainless Steel (Round)	0.45 (Ø)	18
	Stainless Steel (Rectangular)	0.43 × 0.64	17×25
	Stainless Steel (Rectangular)	0.48 × 0.64	19×25

* According to ISO 27020 and ISO 15841 for identifying bracket and wire dimensions.

Clinical cases in the future study will be treated using the same bracket system, wires, molar tubes, and elastic chains as those used in the experimental study.

2.2 Experimental Study

A resin replica model (Technovit 4004, Heraeus Kulzer, Hanau, Germany) of an upper arch, constructed from a Frasaco® model, was utilized. The model was divided into an anterior and a posterior segment behind the canines, with a 5 mm space modeled by removing the first premolars. Brackets were bonded from the second premolar on one side to the second premolar on the opposite side, excluding the removed first premolars.

Figure 2: Frasaco model split up into an anterior and a posterior segment, mounted in the Orthodontic Measurement and Simulation System. The anterior segment is connected to the left force/torque transducer, the posterior to the right one. Simulated space closure is performed along the Z axis.

Another resin model was prepared similarly, but with two brackets bonded to each of the canines and second premolars. This configuration was designed to investigate a wider range of wire dimensions, as the auxiliary slot of the BioQuick® bracket only allows the insertion of a round wire with a maximum diameter of 0.35 mm (descriptor: 14). A total of 14 wire-bracket combinations were tested (see Table 4).

The Orthodontic Measurement and Simulation System (OMSS) was used for this study. The OMSS is a high-precision biomechanical device specifically designed for orthodontic simulations. It consists of two force/torque sensors, each mounted on a 6-axis positioning table. This setup allows for the precise measurement of forces (in Newtons) and moments (torques, in Newton-millimeters) in all three spatial dimensions. Simultaneously, the OMSS tracks the three-dimensional translational displacements (distances, in millimeters) and rotational displacements (angles, in degrees) of the model segments, enabling a comprehensive analysis of tooth movement mechanics. The system has been used frequently in previous similar studies (Bourauel et al., 1992; Drescher et al., 1991; Drescher et al., 1991; Johal et al., 2022b; Sifakakis et al., 2009).

Table 4: Experimental Wire-Bracket Configurations

Configuration Type	Primary Wire	Auxiliary Wire (if any)
Single Wire (1Br)	16	None
	18	None
	17×25	None
	19×25	None
Two Wires, One Bracket (1Br)	16	12
	16	14
	18	12
	18	14
Two Wires, Two Brackets (2Br)	16	12
	16	14
	16	16
	18	12
	18	14
	18	16

The models were mounted on the OMSS, with the anterior segment on the left force/torque sensor and the posterior segment on the right sensor. The center of resistance (CR) for the anterior segment was positioned 5 mm distal and 10 mm apical to the center of the canine brackets. For the posterior segment, the vertical position of the CR was adjusted to 0.5 of the first molar root length, and anteroposteriorly at a ratio of 2:2.4 of the segment length, 1.1 mm distally to the geometric center of the three posterior teeth. Both segments were aligned to form a complete dental arch with extraction sites between the second premolars and canines. Wires were inserted, brackets were closed, and a power chain was attached, applying an initial force of approximately 3.5 N.

The OMSS simulated anterior retraction in incremental steps, measuring force systems at each step until a maximum of 200 simulation steps or until forces and moments dropped below predefined thresholds. Each wire-bracket combination experiment was repeated five times. The initial force, total retraction path, and torque angle (representing tipping) of the ante-rior segment were recorded. Ratios of torque (moment) over retraction and retraction normalized to initial force were calculated for comparison. This approach corresponds to previous studies (Drescher et al., 1991; Johal et al., 2022a; Sifakakis et al., 2010) .

2.3 Data Analysis

Statistical analysis was performed using IBM SPSS Statistics, version 18 (IBM Corporation). Data distribution normality was assessed using the Shapiro-Wilk test. ANOVA, Brown-Forsythe test, and Tukey’s multiple comparisons test were used to determine statistical significance, except for initial forces. The level of significance was set at $p=0.05$.

3. Results

3.1 Mean initial force

The mean initial forces for various bracket/wire combinations ranged from approximately 2.75 N to 5.17 N. This range indicated some variability in the forces applied by different combinations, which was expected due to the inhomogeneity of the power chain used in the study (Fig. 3, Table 5). The ANOVA results indicated no significant differences among the means of the different bracket/wire combinations. The F-value was 1.537, with a P-value of 0.20, which was not significant. The R squared value was 0.5403, suggesting that the variability within the groups was not significantly different from the variability between the groups. The Brown-Forsythe test showed significant differences among the standard deviations, with an F (DFn, DFd) value of 7.708 and a P-value of <0.001. This indicated that there was significant variability in the data, which could be due to the differences in the bracket/wire combinations or other experimental factors.

The Tukey's multiple comparisons test results showed no significant differences among the bracket/wire combinations, with all adjusted P-values greater than 0.05.

The mean differences between combinations are small and not statistically significant. For example, the comparison between 16 1Br and 18 1Br shows a mean difference of 0.3388 with an adjusted P-value greater than 0.99, indicating no significant difference. Overall, the data suggested that the twin guiding arch system provided consistent initial forces across different bracket/wire combinations. This consistency is crucial for achieving predictable and controlled tooth movements in orthodontic treatments. The lack of significant differences among the combinations implies that clinicians can expect similar performance from various configurations, allowing for flexibility in treatment planning.

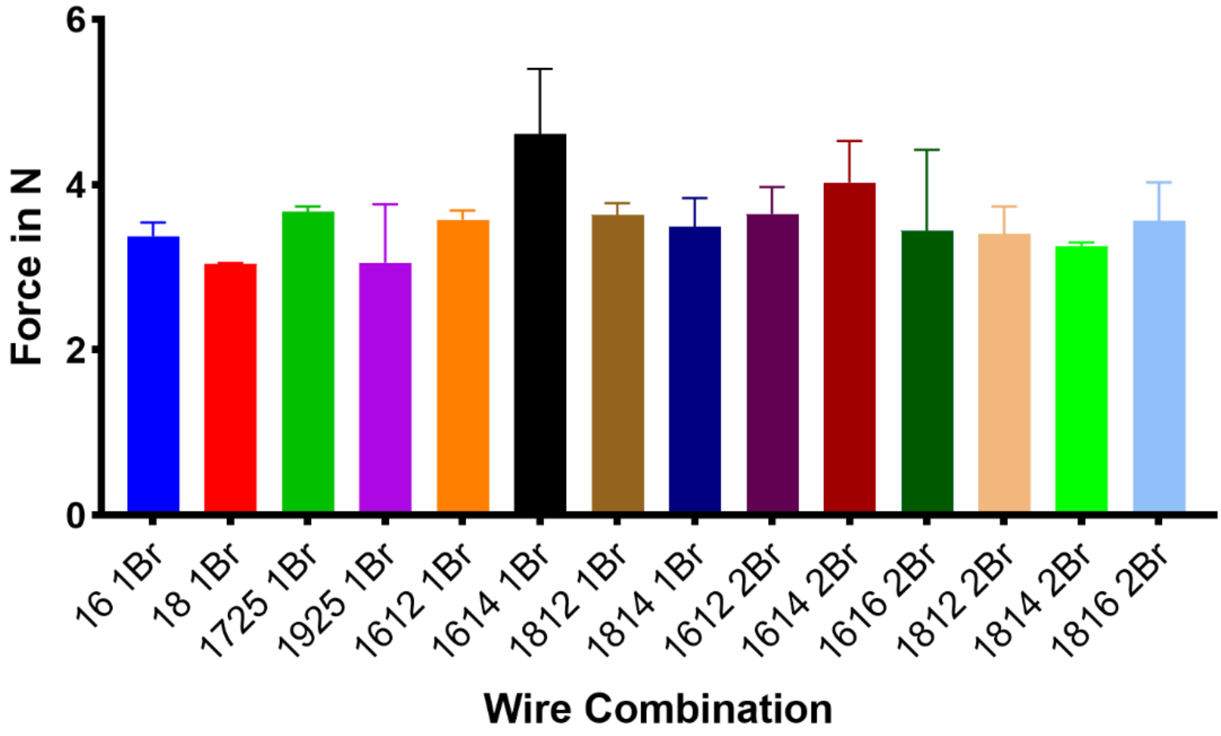

Figure 3: Mean initial force for all measured bracket/wire combinations. Force varies from the 3.5 N, due to inhomogeneity of the power chain. 1Br and 2Br denote measurements with one or two wires in one Quick bracket and two wires in two Quick brackets, respectively.

Table 5: Statistical Summary of Mean Initial Force Analysis

Statistical Test	Parameter	Value	Interpretation
ANOVA	F-value	1.537	
	P-value	0.20	Not significant
	Conclusion	**No significant differences among group means.**	
Brown-Forsythe Test	F (DFn, DFd)	7.708 (13, 17)	
	P-value	<0.001	Highly significant
	Conclusion	**Standard deviations are significantly different.**	
Tukey's Multiple Comparisons	Adjusted P-values	All >0.05	Not significant
	Conclusion	**No significant difference between any two groups.**	

3.2 Total retraction

The retraction data provided included measurements of the total retraction path after stopping simulated retraction for various bracket/wire combinations in the context of sliding mechanics involving a twin guiding arch system (Fig. 4, Table 6, and 7). The combinations ranged from “16 1Br” to “18×16 2Br,” with each combination showing different retraction values. The analysis included an ANOVA test, which revealed significant differences among the means of the different combinations, with an F value of 5.978 and a

P value of less than 0.001, indicating that the differences were statistically significant. The R squared value of 0.8205 suggested a good fit of the model. The Brown-Forsythe test showed no significant differences in standard deviations among the groups, with a P value of 0.93.

Tukey’s multiple comparisons test identified significant differences between certain wire combinations, particularly involving the 19×25 1Br combination, which showed significant differences with several other combinations, such as 16 1Br, 16×12 1Br, and 16×12 2Br. Moreover, details on the multiple comparisons, including the mean differences, standard errors, sample sizes, test statistics, and degrees of freedom, have shown significant differences found between the 16 1Br and 19×25 1Br combinations, as well as between the 19×25 1Br and several other combinations. Non-significant differences were observed in many other comparisons, indicating similar retraction paths among those combinations. Overall, the analysis highlighted the distinct retraction path of the 19×25 1Br combination compared to others, which is crucial for optimizing orthodontic treatments involving a twin guiding arch system.

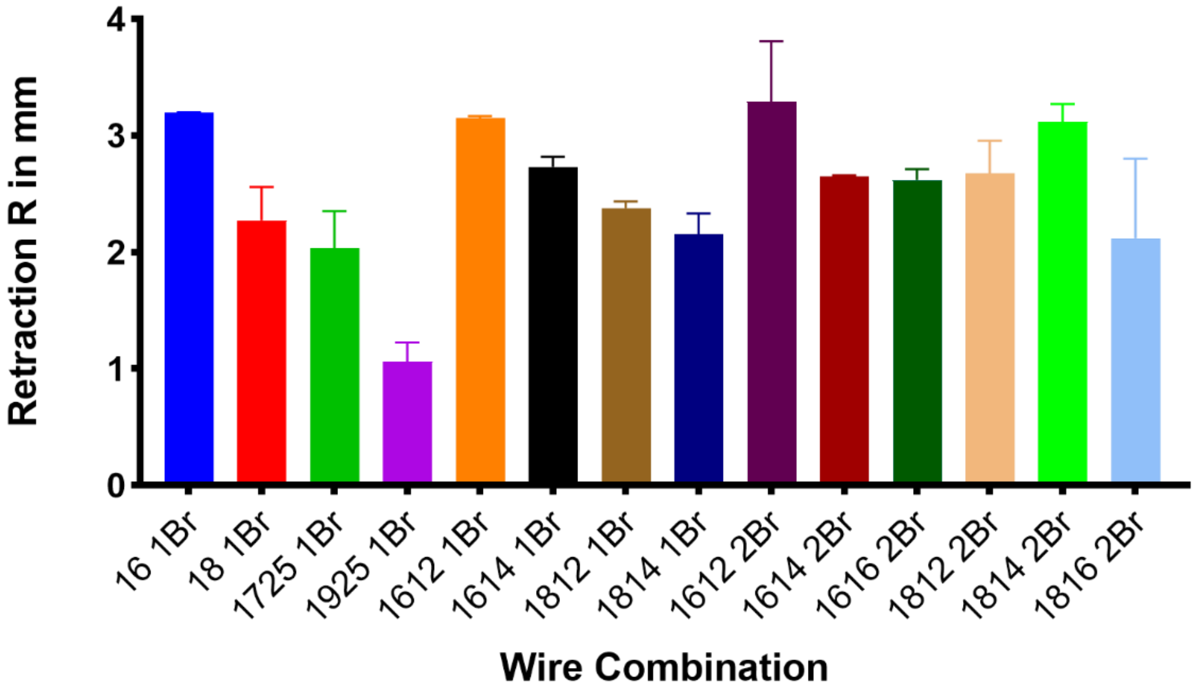

Figure 4: Total retraction path after stop of simulated retraction for all measured bracket/wire combinations. 1Br and 2Br denote measurements with one or two wires in one Quick bracket and two wires in two Quick brackets, respectively.

Table 6: Combined ANOVA Summary for Total Retraction Analysis

Statistical Test	Statistic	Value / Details
ANOVA	F-value	6.243
	P-value	<0.0001 (****)
	R-squared	0.748
	Source	**Sum of Squares**
	Treatment (Between Groups)	11.74
	Residual (Within Groups)	19.37
Brown-Forsyth	P-value	0.0297 (*)

Table 7: Tukey's Test - Selected Significant Comparisons for Total Retraction

Comparison Pair	Mean Difference (mm)	95% Confidence Interval	Significance (Adjusted P-Value)
16 1Br vs. 19×25 1Br	2.137	(0.775 to 3.499)	<0.001 (***)
19×25 1Br vs. 16×12 1Br	-2.091	(-3.453 to -0.729)	<0.001 (***)
19×25 1Br vs. 16×14 1Br	-1.671	(-3.033 to -0.308)	0.009 (**)
19×25 1Br vs. 16×12 2Br	-2.231	(-3.593 to -0.869)	<0.001 (***)
19×25 1Br vs. 18×14 2Br	-2.055	(-3.417 to -0.693)	0.001 (**)

3.3 Anterior Torque Angle Analysis

The analysis of anterior torque angle, representing the degree of tipping of the anterior segment, in different wire combinations revealed significant varia-tions (Fig. 5, Table 8). The ANOVA results showed a significant difference among the means of the wire combinations, with an R squared value of 0.8790, indicating that the model explained a substantial proportion of the variance. The F value was 9.498 with a P value < 0.001, confirming significant differences between groups. The Brown-Forsythe test supported the homogeneity of variances assumption, with an F value of 0.5524 and a P value of 0.86, indicating no significant difference in variances. Tukey's multiple comparisons test identified significant differences in anterior torque angle between specific wire combinations. For example, "16 1Br" showed significant differ-ences when compared to "17×25 1Br" (mean difference of 9.185, P < 0.001) and

"19×25 1Br" (mean difference of 11.22, P < 0.001). Other notable comparisons included "16 1Br" vs. "18×12 2Br" and "16 1Br" vs. "18×16 2Br" (mean difference of 6.017, P = 0.006). These findings underscore the importance of selecting the appropriate wire combination for effective orthodontic treatment, providing valuable insights for optimizing treatment plans.

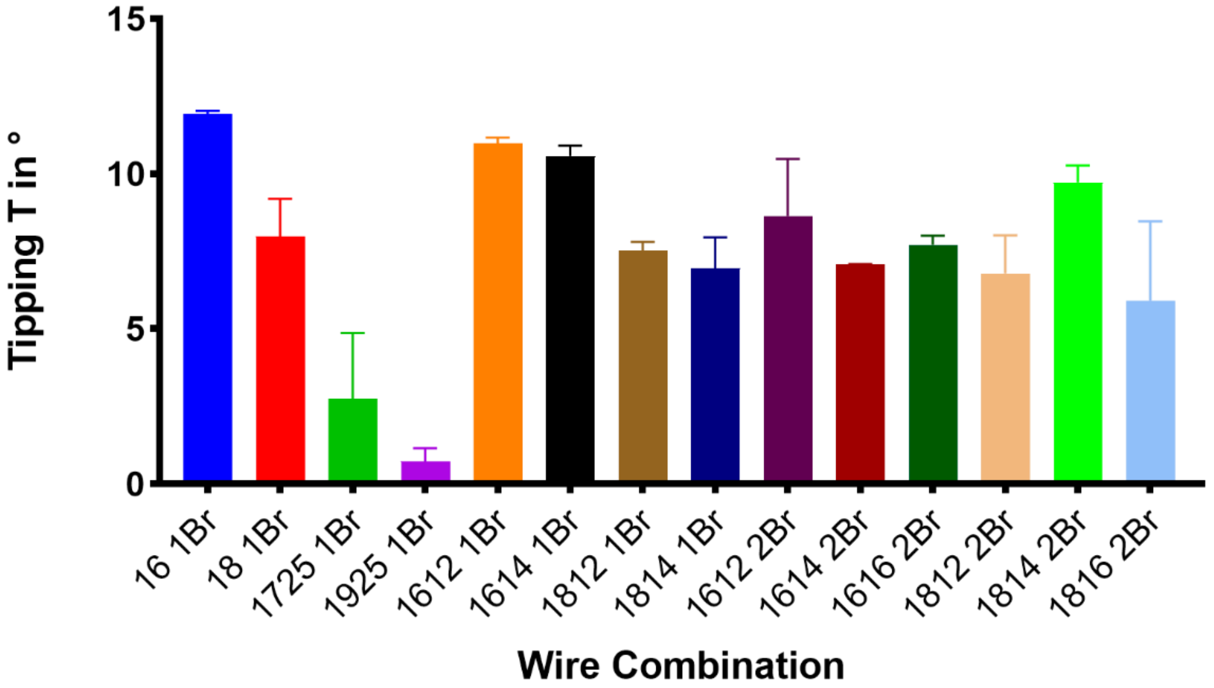

Figure 5: The analysis of anterior torque in different wire combinations. 1Br and 2Br denote measurements with one or two wires in one Quick bracket and two wires in two Quick brackets, respectively.

Table 8: Statistical Summary of Anterior Torque Angle Analysis

Statistical Test	Statistic	Value	Conclusion
ANOVA	F-value P-value	9.498 <0.001 (***)	**Significant differences among group means.**
Selected Comparisons (Tukey's)	**Mean Difference (deg)**	**P-value**	
16 1Br vs. 17×25 1Br	9.18	<0.001	Significant
16 1Br vs. 19×25 1Br	11.22	<0.001	Significant
18 1Br vs. 19×25 1Br	7.27	0.004	Significant
19×25 1Br vs. 16×12 1Br	-10.27	<0.001	Significant

3.4 Torque per Retraction (T/R) ratio

This study on sliding mechanics involving a twin guiding arch system revealed signifi-cant differences in torque (moment) per retraction (T/R) among various bracket/wire combinations (Fig. 6, Table 9). The ANOVA results showed a highly significant difference ($F = 16.05$, $P < 0.001$) with an R squared value of 0.9246, indicating that the model explains a large portion of the variance. Tukey's multiple comparisons test highlighted that com-binations like 16 1Br vs. 17×25 1Br (Mean Diff. = 2.447, $P < 0.001$) and 16 1Br vs. 19×25 1Br (Mean Diff. = 3.084, $P < 0.001$) had substantial differences. Hence, the 1Br configurations generally showed higher torque values compared to the 2Br configurations. For instance, 16 1Br had higher torque per retraction compared to 16×12 2Br (Mean Diff. = 1.116) and 16×14 2Br (Mean Diff. = 1.054). This suggests that the single bracket (1Br) configurations might result in higher torque per retraction.

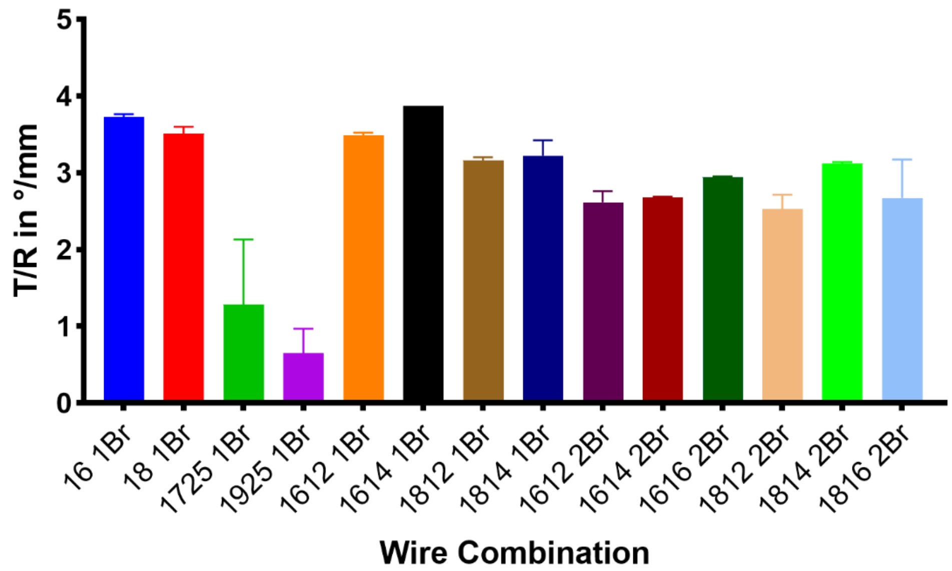

Figure 6: differences in torque per retraction (T/R) among various bracket/wire combinations. 1Br and 2Br denote measurements with one or two wires in one Quick bracket and two wires in two Quick brackets, respectively.

Table 9: Statistical Summary of Torque-per-Retraction (T/R) Ratio

Statistical Test	Statistic	Value	Conclusion
ANOVA	F-value	16.05	
	P-value	<0.001 (***)	**Significant differences among group means.**
Selected Comparisons (Tukey's)	**Mean Difference (Nmm/mm)**	**P-value**	
16 1Br vs. 17×25 1Br	2.447	<0.001	Significant
16 1Br vs. 19×25 1Br	3.084	<0.001	Significant
18 1Br vs. 19×25 1Br	2.861	<0.001	Significant
17×25 1Br vs. 16×12 1Br	-2.201	<0.001	Significant

3.5 Retraction per initial force (R/F) ratio

Within this study, retraction normalized to applied force for various bracket/wire combinations was analyzed. The data showed significant differences among the means (ANOVA F-value: 5.447, P-value: <0.001, R-squared: 0.8064) (Fig. 7, Table 10). TTukey's multiple comparisons test revealed significant differences, particularly between 16 1Br and 19×25 1Br, and 19×25 1Br and 16×12 1Br. The 19×25 1Br combination consistently showed lower retraction values, indicating less effectiveness, while 16 1Br and 16×12 2Br showed higher retraction values, suggesting better performance. The q-values and Mean Diff. highlighted the statistical significance of these differences, with higher q-values indicating stronger evidence against the null hypothesis. Additionally, significant differences were found between 19×25 1Br and 16×12 2Br (Mean Diff.: -0.5500, q: 7.236), and 19×25 1Br and 18×14 2Br (Mean Diff.: -0.6065, q: 7.979). The 18×14 2Br vs. 18×16 2Br comparison also showed a significant difference (Mean Diff.: 0.3667, q: 5.571). These results suggest that the 19×25 1Br combination is less effective in retraction, while 16 1Br, 16×12 2Br, and 18×14 2Br combinations demonstrate better performance.

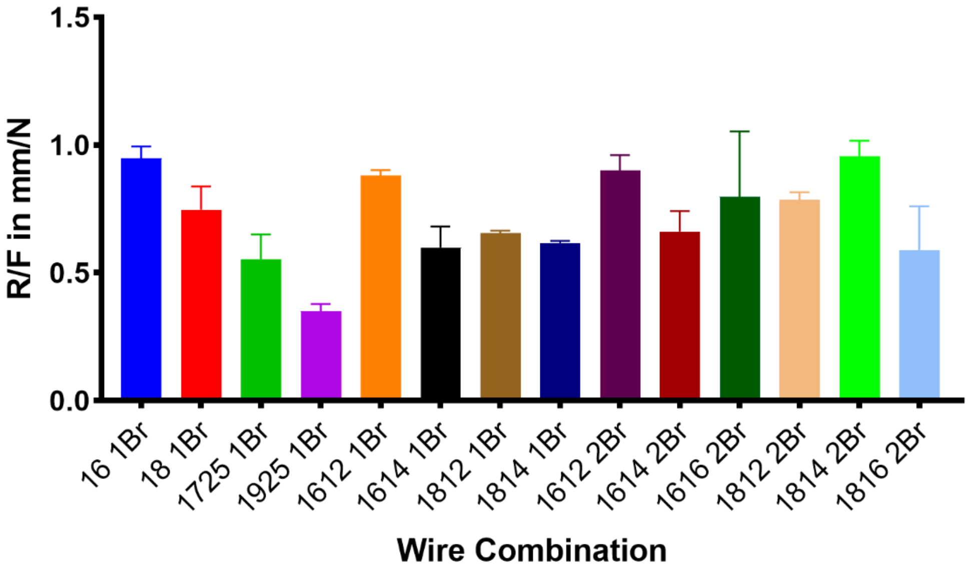

Figure 7: Retraction normalized to applied force for various bracket/wire combinations. 1Br and 2Br denote measurements with one or two wires in one Quick bracket and two wires in two Quick brackets, respectively.

Table 10: Statistical Summary of Retraction-per-Force (R/F) Ratio

Statistical Test	Statistic	Value	Conclusion
ANOVA	F-value	5.447	
	P-value	<0.001 (***)	**Significant differences among group means.**
Selected Comparisons (Tukey's)	**Mean Difference (mm/N)**	**P-value**	
16 1Br vs. 19×25 1Br	0.5975	0.002	Significant
19×25 1Br vs. 16×12 1Br	-0.5308	0.006	Significant
19×25 1Br vs. 16×12 2Br	-0.5500	0.004	Significant
19×25 1Br vs. 18×14 2Br	-0.6065	0.002	Significant

4. Discussion

4.1 Discussion of Results

The goal of this study was to investigate the biomechanical efficacy of a twin guiding arch system, and the results provide a clear rationale for clinical decisionmaking based on specific treatment objectives. The primary clinical goals during anterior retraction are typically threefold: (1) controlling incisor torque to achieve bodily movement and prevent undesirable tipping, (2) ensuring efficient and predictable space closure, and (3) preserving posterior anchorage. The tested wire combinations demonstrated distinct advantages in relation to these goals.

For achieving maximum torque control and promoting bodily tooth movement, the stiffer, single rectangular wire configurations, particularly 19×25 1Br and 17×25 1Br, were found to be most effective. These combinations generated the highest torque angles and the highest torque-per-retraction (T/R) ratios. A high T/R ratio is clinically significant because it indicates that a greater portion of the retraction force is being effectively converted into a rotational moment, which is essential to counteract the natural tendency of the incisors to tip lingually during retraction. The clinical advantage of using a 19×25 wire, for instance, is its ability to fully engage the bracket slot, minimizing wire-slot play and providing rigid control over root position. This makes it the superior choice for cases where maintaining or increasing incisor torque is a primary aesthetic or functional goal.

Conversely, for treatment plans prioritizing the speed and efficiency of space closure, other combinations proved more advantageous. The data revealed that combinations like 1612 2Br and 16 1Br yielded the greatest total retraction paths. This is reflected in the high retraction-per-initial-force (R/F) ratios for these groups. Clinically, this means these systems are more efficient at closing space, as they exhibit lower frictional resistance and allow for greater sliding. The specific advantage of a dual-wire system like 1612 2Br may lie in its ability to distribute forces while maintaining a lower overall stiffness compared to a large single wire, thus facilitating smoother movement. However, this increased retraction efficiency comes at the cost of reduced torque control, as evidenced by their lower T/R ratios. Therefore, these combinations are best suited for cases where minor tipping is acceptable or even desired.

Ultimately, the findings underscore that the choice of wire combination is not a onesize-fits-all decision but should be tailored to the specific biomechanical demands of each case. For a patient requiring significant bodily movement of the anterior segment with maximum anchorage preservation, a large-dimension, single rectangular wire (e.g., 19×25) is biomechanically justified. For a patient where rapid space closure is the priority and torque requirements are minimal, a more flexible system, such as a smaller single wire or a dual-wire combination, would be the more efficient clinical choice.

4.2 Discussion of Materials and Methods

One significant source of error in this study is the variability in wire/slot play. Differences in the dimensions of wire pieces, even within the same alloy and cross-section, led to variations in slot play across the four appliances, affecting the recorded values. To reduce random error, multiple repetitions were conducted. The Orthodontic Measurement and Simulation System (OMSS) has a maximum sensor error of 0.3 % in linearity and 1.8 % due to cross-talk (Bourauel et al., 1992). Additional potential sources of error include inaccuracies in model scanning, duplication methods, and statistical errors from repetitions. Despite these potential errors, scanning and duplication of stone casts using silicone molds have been demonstrated to be precise (Amuk et al., 2019; Kirschneck et al., 2018). Although human error cannot be entirely quantified, all procedures were consistently performed by the same investigator to maintain uniformity.

4.3 Discussion in the Light of Literature

The biomechanical findings of this in-vitro investigation contribute to a nuanced and complex area of orthodontic research: the interplay between efficiency, friction, and torque control in sliding mechanics. A central theme emerging from recent literature is the ongoing debate regarding the clinical superiority of various bracket and wire systems. The present study's core conclusion, that a fundamental tradeoff exists between the retraction efficiency offered by flexible systems and the torque control provided by stiffer ones, can be effectively contextualized within this scientific discourse.

The principle of resistance to sliding is foundational to the efficiency of space closure. A comprehensive review by Rinchuse and Cozzani (Rinchuse et al., 2015) elaborates that this resistance is a multifactorial phenomenon composed of classical friction, binding, and notching. A recent scoping review by Cernei et al. (Cernei et al., 2023) critically evaluated the claims of enhanced efficiency for passive selfligating brackets (PSLBs), which are marketed for their low-friction properties. Their analysis of 39 studies concluded that clinical evidence remains equivocal; most studies found no significant differences in space closure rates or overall treatment duration when comparing PSLBs to active self-ligating brackets (ASLBs) or conventional brackets (CBs). Similarly, a systematic review by Chen et al. (Chen et al., 2010) also found insufficient clinical evidence to support claims of faster treatment with self-ligating systems. This broader context aligns with this dissertation's finding that flexible wire combinations (such as smaller single wires or the tested dualwire setups) yielded greater retraction paths. The reduced stiffness likely minimized binding, often a greater contributor to resistance than friction, thereby facilitating more efficient sliding. This is further supported by an in-vitro study from Al-Dulaimi et al. (Al-Dulaimi et al., 2025), which demonstrated that passive SLBs generated the lowest static frictional resistance compared to active SLBs and conventional brackets, reinforcing the mechanical principle that less active engagement can lead to smoother sliding.

However, this pursuit of low friction is biomechanically incomplete without considering the imperative of torque control. The review by Cernei et al. (Cernei et al., 2023) noted conflicting evidence regarding incisor torque control among different bracket systems. The present dissertation’s finding, that superior torque control was achieved with stiffer, single rectangular wires like 0.019”x0.025”, directly addresses this issue. A finite element method (FEM) study by Thote et al. (Thote et al., 2020) provides strong theoretical validation for this, concluding that a 0.019”x0.025” stainless steel archwire was the optimal combination for generating the necessary torque for bodily en-masse retraction. This confirms the mechanical necessity of using large-dimension wires that can fully engage the bracket slot to express a therapeutic moment. In a recent clinical trial, Le et al. (Le et al., 2025) compared friction-based sliding mechanics with frictionless T-loop mechanics and concluded that the T-loop provided superior torque control. This implies that sliding mechanics present an inherent challenge to maintaining torque, thus highlighting the critical importance of selecting a stiff, slot-filling archwire, even if it leads to less efficient retraction.

This speed-versus-control trade-off, demonstrated in this in-vitro experiment, has a compelling clinical analogue. A split-mouth randomized controlled trial by Kassas et al. (Kassas et al., 2025) compared direct sliding (DS) to canine brackets against power arm sliding (PAS) using mini-implant anchorage. They found that the total retraction rate was significantly faster with the DS method. However, the PAS method, which applies the force closer to the center of resistance, provided significantly better control, resulting in less unwanted tipping and rotation. This clinical study perfectly mirrors the findings of the present investigation: mechanics optimized for speed may sacrifice control, while mechanics designed for control are often less efficient. The choice of a wire combination in sliding mechanics therefore represents a deliberate clinical decision to prioritize one of these competing objectives.

This study's investigation into a twin guiding arch system also contributes to the literature on innovative biomechanics. While dual-wire systems are not widespread, related concepts have been explored. A recent FEM study by Kuga et al. (Kuga et al., 2024) investigated a dual-dimensional archwire (with a larger anterior crosssection) and found it provided better controlled movement and torque expression of the incisors compared to a conventional rectangular archwire. This computational finding provides strong parallel evidence supporting the hypothesis that using a dual-wire system can be an effective strategy for modulating the force system at the bracket-wire interface. Furthermore, the methodology used in the present dissertation is validated by other high-quality in-vitro studies. Johal et al. (Johal et al., 2022), for example, utilized the same Orthodontic Measurement and Simulation System (OMSS) to test a novel Tip and Torque Adjustable Bracket, reaffirming the system's validity for precisely measuring forces, moments, and retraction rates. The broader context of such laboratory research is discussed by Sifakakis and Eliades (Sifakakis et al., 2017), who reviewed laboratory methods in orthodontic biomechanics and affirmed the value of in-vitro trials for isolating biomechanical variables, while rightly cautioning against direct clinical extrapolation without considering biological factors like the periodontal ligament.

Finally, the literature suggests that the specifics of the bracket's ligation mechanism (i.e., active versus passive) may be a secondary factor compared to the archwire-slot interaction. A randomized controlled trial by Abu-Shahba and Alassiry (AbuShahba et al., 2019) found no statistically significant difference in the rate of canine retraction or anchorage loss between active and passive SLBs. This clinical finding, along with a similar conclusion from a trial by Pandis et al. (Pandis et al., 2010) on alignment efficiency, suggests that the wire dimension and material properties, the primary variables in this dissertation, are likely the more dominant determinants of the mechanical outcome.

In summary, the findings of this dissertation are well-supported within the scientific literature. They highlight a fundamental biomechanical compromise between retraction efficiency and torque control. While the debate over the superiority of any single bracket system is ongoing, a stronger consensus is emerging that a clinician’s choice of archwire size and material is paramount. The present work provides foundational biomechanical data for a novel dual-wire system, suggesting that tailored wire combinations can offer clinicians a versatile toolkit to meet specific, and often competing, treatment goals.

4.4 Limitations

While this *in vitro* study provides valuable foundational data on the biomechanics of a twin guiding arch system, its limitations must be explicitly acknowledged. The primary limitation is the experimental nature of the investigation, which, while offering precise control over mechanical variables, cannot fully replicate the complex biological environment of the oral cavity. Biological factors such as the viscoelastic response of the periodontal ligament (PDL), bone remodeling, tooth mobility within the dental arch, and the influence of masticatory and soft tissue forces were not accounted for in this simulation. As Sifakakis and Eliades (Sifakakis and Eliades, 2017) emphasize in their critical review, results from ex-vivo investigations should not be directly extrapolated to clinical practice without skepticism, as they do not capture these essential biological dynamics.

Furthermore, this study was conducted in a dry state. Previous studies have demonstrated that the presence of saliva can alter the frictional characteristics at the bracket-wire interface, though the extent of this effect remains a point of debate in the literature (Thorstenson et al., 2001). Additionally, the use of pre-formed, idealized resin models does not account for the anatomical variability in tooth morphology and alveolar bone topography found in human patients, which can significantly influence force expression and tooth movement patterns.

Finally, because this research is foundational, it lacks long-term clinical data to validate the observed biomechanical trade-offs. The conclusions drawn about torque control versus retraction efficiency are based purely on mechanical measurements of force, moment, and displacement. A definitive assessment of the twin guiding arch system's clinical utility would require prospective, randomized controlled trials that measure patient-centered outcomes, long-term stability, and potential adverse effects such as root resorption. Therefore, the findings of this dissertation should be considered a preclinical biomechanical proof of concept, which serves as a necessary and informative precursor to essential future clinical investigation.

4.5 Conclusion

Based on this comprehensive *in vitro* biomechanical investigation, it can be concluded that the twin guiding arch system, like conventional sliding mechanics, operates on a fundamental trade-off between retraction efficiency and torque control. This study successfully quantified the distinct mechanical behaviors of various single- and dual-wire combinations and provided robust evidence for the following principles:

1. Stiffer, single rectangular archwires that more fully engage the bracket slot are biomechanically superior for generating the torque moments required for controlled bodily tooth movement. However, this rigidity inherently increases resistance to sliding, resulting in less efficient space closure.

2. More flexible wire combinations, including smaller single wires and dual-wire setups, demonstrate significantly greater retraction efficiency. This is attributed to reduced binding and friction, but it comes at the cost of diminished torque control, leading to a greater degree of unwanted tipping. The clinical implication of these findings is that the selection of an archwire-bracket configuration should be a deliberate, goal-oriented decision rather than a standardized protocol. This study provides a foundational mechanical rationale that equips orthodontists to tailor their approach: for cases demanding maximum control over incisor inclination, a stiff, slot-filling wire is indicated, whereas for cases prioritizing speed where some tipping is acceptable, a more flexible system is more efficient. The twin guiding arch system, therefore, does not represent a single “superior” solution but rather a versatile clinical tool that offers a spectrum of biomechanical options. Ultimately, while this experimental study has established a clear proof of concept, prospective clinical trials are essential to validate these findings and determine the system’s true clinical effectiveness, long-term stability, and impact on patient outcomes.

5. Summary

This thesis presents an *in-vitro* experimental investigation into the biomechanical efficacy of a twin guiding arch system for the retraction of maxillary anterior teeth. The study's primary goal was to provide a foundational mechanical analysis of this novel technique by precisely measuring how different wire combinations affect torque control, frictional resistance, and the overall efficiency of space closure.

The introduction outlined the clinical challenge of retracting anterior teeth following premolar extractions, a procedure that demands a delicate balance between efficient space closure and the precise control of incisor torque to achieve optimal functional and aesthetic outcomes. Conventional sliding mechanics often present a biomechanical compromise between these two objectives. This study proposed that a dual-wire configuration within a self-ligating system might offer a more versatile approach to managing this compromise.

In the materials and methods section, resin models of the maxilla with simulated extraction spaces were created. A self-ligating bracket system with auxiliary slots was used to test fourteen distinct wire-bracket combinations, including single rectangular wires, single round wires, and various dual-wire setups. Using the highly precise Orthodontic Measurement and Simulation System (OMSS), variables including retraction distance, moments (torque), and the resultant torque angle (tipping) were measured under simulated retraction forces. The data were then analyzed to compare the performance of each configuration.

The results of this study demonstrated a clear and clinically relevant biomechanical trade-off. It was determined that no single wire combination was universally superior; rather, the optimal setup was dictated by the specific clinical priority:

1. For achieving maximum torque control, which is essential for bodily tooth movement, stiffer single rectangular archwires (e.g., 0.019”x0.025”) were most effective. These configurations generated the highest torque moments, best resisting the unwanted lingual tipping of the incisors during retraction.

2. For maximizing retraction efficiency and speed, more flexible systems, such as smaller single wires and certain dual-wire combinations, were superior. These setups produced less resistance to sliding, resulting in a greater retraction distance for the applied force.

The discussion contextualized these experimental findings within the broader scientific literature. The observed trade-off between control and speed aligns with results from both finite element analyses and clinical trials comparing different orthodontic mechanics. It was argued that, when compared to other systems described in the literature, the true advantage of a versatile system like the twin guiding arch lies not in a single “superior performance,” but in its potential to provide clinicians with a wider range of biomechanical options. By selecting specific wire combinations, practitioners can tailor the mechanics to prioritize either rigid torque control for complex cases or low-friction efficiency for simpler ones.

The study concluded by emphasizing its primary limitation as a laboratory-based investigation and underscored the critical need for future prospective clinical trials to validate these findings in patients.

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9. Statement on personal contributions

The work was carried out at the Biomechanics laboratory of the Oral Technology of the University of Bonn under the supervision of Prof. Dr. rer. nat. Christoph Bourauel.

The concept of the study was developed by the author of the thesis in collaboration with Prof. Dr. Christoph Bourauel, Head of Oral Technology.

All experiments were carried out by me with support from Prof. Dr. Bourauel.

The statistical analysis was carried out under my guidance by the statistical expert Mr. Ali Ahmadi (Teheran, Iran).

While preparing this work, I used ChatGPT-3.5 to improve the readability and language of the thesis. After using this tool, I reviewed and edited the corresponding paragraphs as needed and take full responsibility for the content of the published doctoral thesis.

I confirm that I have written this doctoral thesis independently and that I have listed all sources and resources used.

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