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RESEARCH ARTICLE

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Force behaviour of elastic chains during a simulated gap closure in extraction therapy cases

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Abstract

Objective: Tooth movement with elastic chains requires defined force magnitudes. This study assessed the force behaviour of different elastic chains at different configurations of gap width.

Methods: Self-ligating brackets of teeth 5 & 6 and 2 & 3 were bonded to two movable aluminium plates. The plates were positioned on a joint basis with varying distances of 0.5, 2.0, 4.0, 6.0, and 8.0 mm. Reset forces of open and closed chains from four different manufacturers were investigated in four different configurations. Configurations differed in either having an additional intermediate ring within the gap (#1, #3) and/or having intermediate rings between teeth adjacent to the gap (#1, #2), or by no intermediate rings (#4). Forces were measured with a universal testing machine. The results were statistically analysed using U-test, H-test and (if applicable) post-hoc tests with a significance level of .05.

Results: Configurations #1 and #3, and #2 and #4 formed homogenous subgroups ($P < .001$). Initial forces in configuration #4 were significantly higher than in configuration #3 ($P = .029$). Initial forces in closed chains were significantly higher than for open chains ($P = .029$).

Conclusions: Intermediate chain rings adjacent to the gap are not required to modulate the force. In contrast, leaving a ring unapplied in the tooth gap can help modulate the force. Open thermoset chains with an additional ring within the gap (#3) seem to produce suitable initial forces for a gap closure of 4 mm. With a residual gap width of <2 mm, open thermoset chains and closed thermoset chains (#4) seem suitable.

KEYWORDS
chain configuration, extraction therapy, gap closure, orthodontic chains, sliding mechanics

1 | INTRODUCTION

In this study, we focus on the application of orthodontic elastic chains for gap closure in sliding mechanics. Sliding mechanics are commonly applied in extraction therapy after extraction of the first premolar due to crowding.[1] For the sake of completeness, gap closure can also be achieved by frictionless mechanics, in which loops are bent into the wire to close spaces.[2] Biomechanically, the orthodontic chain is fixed to brackets coronally of the centre of resistance, and serves as a central source of force for gap closure.[1]

Tooth movement with orthodontic chains requires precisely defined forces during treatment.[3] Precise force application with orthodontic chains is problematic, as they show variations in force decay depending on their polymeric material.[4,5] Within the first hour after application, chains made from thermoplastic polyurethane (TPU) show a relative force decay of 40%-50%, and chains made from thermoset polyurethane (TSU) of 20%-25%.[5] After 21 days the force decay of TPU chains was 65% and that of TSU chains 25%-30%.[4] Little is known about forces exerted by different types of orthodontic elastic chains in different clinical configurations with closed (i.e. no inter-modular link) or open (i.e. with inter-modular link) chain types employed.[6] Additionally, the clinician can leave chain rings between brackets unapplied to modulate the resulting force.[7] Force measurements with a gauge are rarely done in the day-to-day practice and can be time consuming and imprecise. The application of excessive forces can lead to indirect resorption and increase the risk of root resorption.[8–11] Additionally, negative effects on tooth movement might occur and the duration of treatment may be prolonged.[1] Hence, there is a need for a pragmatic and practical guideline, which is easy to integrate into the clinician's existing workflows.

Therefore, this study aimed to assess the forces exerted by different chain configurations during simulated closure of minor gaps width up-to-gap widths in extraction therapy cases (0.5-8.0 mm). We hypothesized that the force exerted by orthodontic elastic chains is identical, independent of the width of the tooth gap and usage of open or closed chains. Additionally, we hypothesized that the force exerted by orthodontic elastic chains is identical, independent of both chain configuration (i.e. leaving rings between brackets unapplied) and chain suppliers.

2 | MATERIALS AND METHODS

2.1 | Chain configurations

In this study, a setup was designed to simulate a clinical gap closure of varying distances using different elastic power chain types and configurations (Table 1, Figure 1). The simulated gaps may represent gaps between lateral incisor and canine or between canine and premolar, as well as between first molar and premolar. The effect of archwire friction and binding is intentionally neglected in order to isolate the initial forces of the chains in different configurations from frictional forces.

To simulate a possible clinical situation, "In-Ovation® R" self-ligating brackets (Dentsply Sirona) of teeth 6, 5, 3, and 2 were bonded to two aluminium plates (Figure 1) as follows. One fixed aluminium plate provided the basis for brackets 6 and 5, and the other movable aluminium plate provided the basis for brackets 4 and 3. Inter-bracket distance (as measured from the adjacent edges of the bases) was 5 mm, which corresponds to a clinical situation with morphological proximal contacts. Since the plates were positioned on a joint acrylic basis, the distance between brackets 5 and 3 was varied at defined steps of 0.5, 2.0, 4.0, 6.0, and 8.0 mm (Figure 2). Initially, the inter-bracket distance between brackets 5 and 3 was set to 13 mm to simulate an 8 mm clinical gap width after premolar extraction.

Elastic reset forces of the power chains were investigated in four different configurations ("B" – elastic ring with bracket; "O" – elastic ring without bracket) (Figure 1):

1. B-O-B-O-B-O-B: every other chain ring was applied to a bracket;
2. B-O-B-B-O-B: one chain ring between brackets 6 and 5 and one ring between brackets 3 and 2 was left unapplied;
3. B-B-O-B-B: one chain ring between brackets 5 and 3 remained unapplied;
4. B-B-B-B: each chain ring was pulled over a bracket; no ring was left between the brackets.

2.2 | Pull testing of chains

The modified pull test was performed with a universal testing machine (Model 5542, Instron Corp.) and load cell (2530-416, Instron Corp.). The testing machine has a measuring range of 0-500 N and can measure with a precision of five decimal places; however, only the first two decimal places were taken into account in the measurements. Forces were measured after the elastic power chains were applied to the brackets and incubated in distilled water at 37°C for 1 min. Incubation was performed to simulate the clinical situation after the initial contact of the orthodontic chain

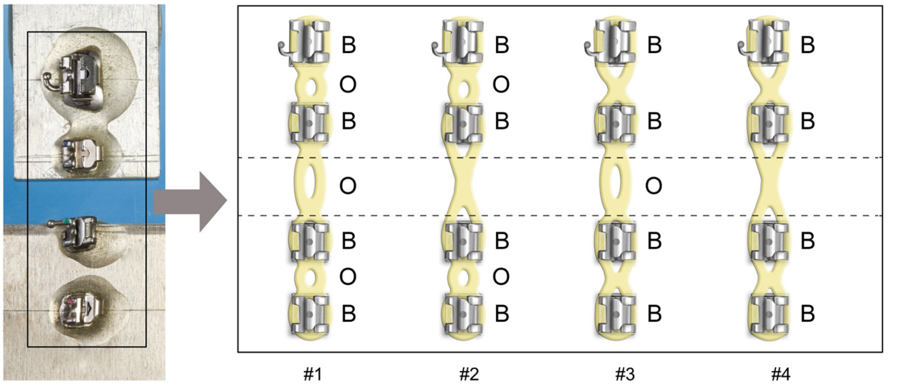
TABLE 1 Chains of the following manufacturers were used in this study

Brand	Manufacturer	Material	Batch No. (open)	Batch No. (closed)
Plastic chain	AO, Sheboygan, WI, USA	TPU	C78295	C67298
Elastic power chain	Forestadent, Pforzheim, BW, DE	TPU	65 500 172	32 303 684
Energy chain	RMO, Denver, CO, USA	TSU	05105	04187
Power chain generation II	Ormco, Orange, CA, USA	TSU	15G63	15H46

Note: Information according to the manufacturer unless otherwise specified. All chains were used in "open" and "closed" configurations.

Abbreviations: TPU, thermoplastic polyurethane; TSU, thermoset polyurethane.

FIGURE 1 Specimen design of the in-vitro clinical study. (Left) Photograph of bracket positions before chain application. (Right) Schematic drawing of chain configurations #1 to #4 from left to right. The dotted lines indicate the margins of the aluminium plates ("B" – elastic ring with bracket; "O" – elastic ring without bracket).



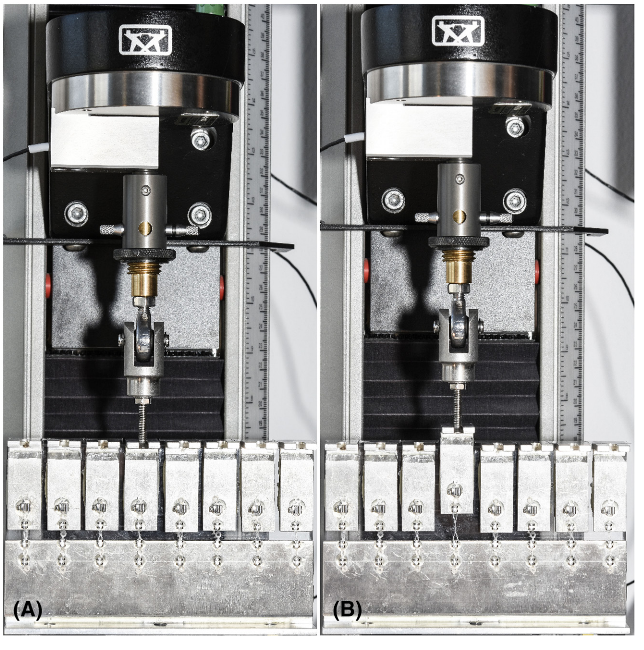


FIGURE 2 Universal testing machine with clamped test plate of the clinical trials (A, left) and with a simulated gap of 8 mm (B, right). Note that the upper plates with brackets 5 and 6 are movable, whereas the bottom plate with brackets 3 and 2 is fixed onto the acrylic base

with saliva in the oral cavity. Afterwards, aluminium plates were applied to the testing machine with a distance of 5 mm between brackets 5 and 3 (=no gap between the teeth). Then, this distance was increased to 13 mm (representing an 8 mm gap width), before returning to its starting point of 5 mm (=gap closure) with a speed of 2.5 mm/s. Thus, the same level of pre-stretching was performed for each individual chain tested. During gap closure, force data recording was done with a frequency of 50 Hz. This way, the forces acting on the brackets during gap closure up to 8 mm were simulated. In clinical terms, the pulling force of the elastic chains was measured from the beginning of the gap closure therapy (gap width = 8 mm). Measured data was processed with Bluehill 3 software (Instron Corp.). For evaluation, the forces were determined at pre-defined discrete steps (8; 6; 4; 2; 0.5 mm) until the gap was almost completely closed (0.5 mm).

2.3 | Statistics

Statistical analysis was done using IBM SPSS Statistics Version 25 (IBM Corp.). Measurements were reported using mean, standard deviation, median, minimum, and maximum. To examine the differences between open and closed chain types of a given configuration and manufacturer on chain force, Mann-Whitney's U test was applied. The Kruskal-Wallis test was used to examine the differences in the effect of different configurations and of different manufacturers on chain force. Post-hoc tests were calculated if applicable, and Bonferroni correction was applied to correct for multiple testing. As significance level $P < .05$ was assumed.

3 | RESULTS

3.1 | Effect of configurations #1 to #4, and gap width on initial mean forces

The initial mean forces of closed and open chains of each manufacturer tested in all configurations are summarized in Figure 3. Independent of the simulated clinical configuration, an almost linear relationship between gap width and resulting force was observed. Averaging the measured forces over all gap widths, configurations #1 and #3 and #2 and #4 formed homogenous subgroups according to post-hoc pairwise comparisons (Kruskal-Wallis; $P < .001$) (Table 2). Hence, we focused on configurations #3 and #4 in the remaining part of this section (see discussion for further details).

3.2 | Comparison of configurations #3 and #4, and of open versus closed chains

Descriptive statistics of the closed and open orthodontic chains in configurations #3 and #4 at different gap widths was summarized in Table 3. Initial forces in configuration #4 were significantly higher than in configuration #3 regardless of the chain type, gap width, or manufacturer ($P = .029$), except for the elastic chains from AO at a gap width of 2 mm ($P = .057$). Initial forces in closed chains were

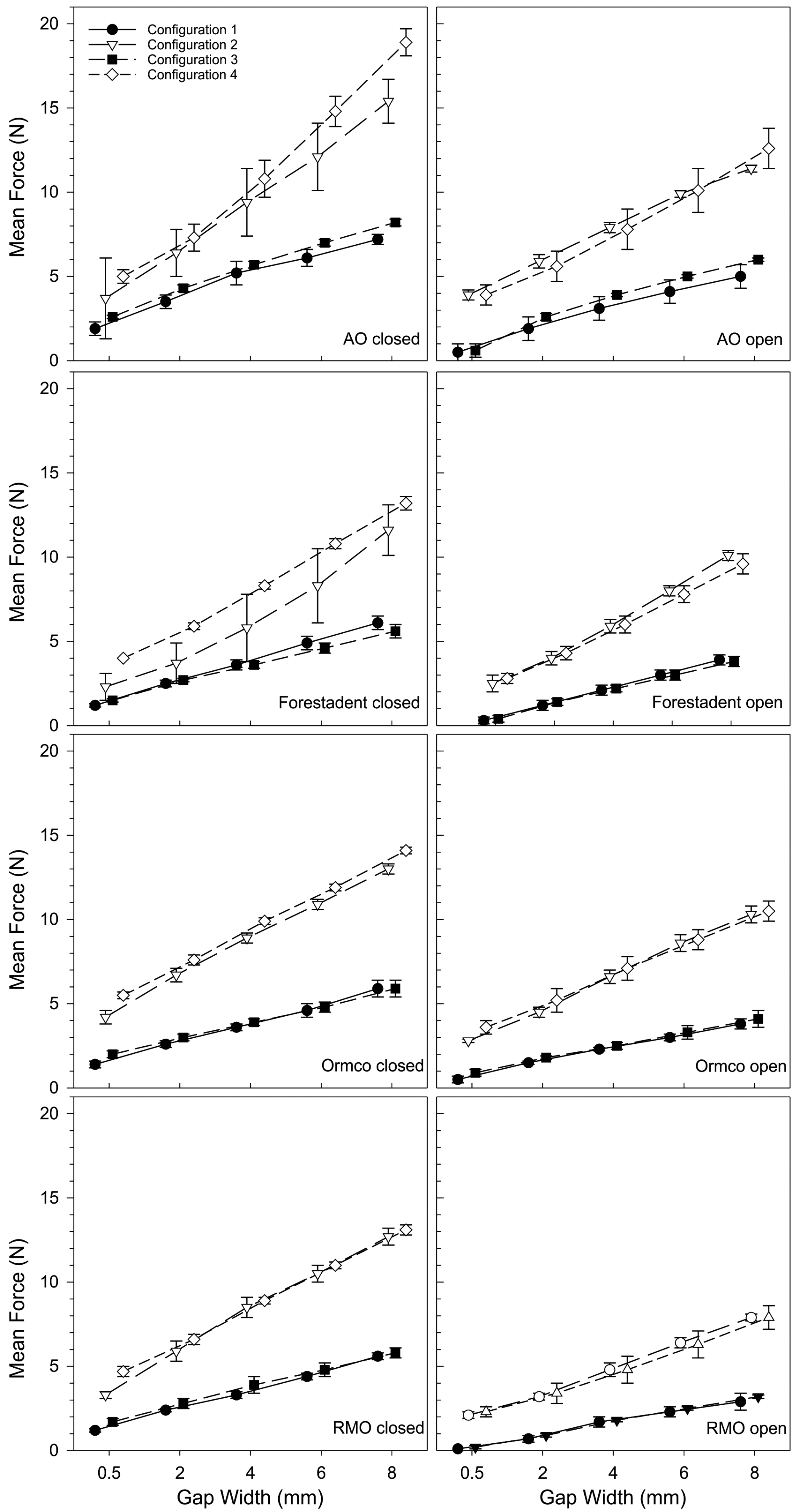

Configuration 1
Configuration 2
Configuration 3
Configuration 4
Mean Force (N)
Gap Width (mm)
0.5
2
4
6
8
0
5
10
15
20
AO closed
AO open
Forestadent closed
Forestadent open
Ormco closed
Ormco open
RMO closed
RMO open

FIGURE 3 Initial mean forces (±SD) of both open (right) and closed chain (left) types at different simulated gap widths in configuration #1-#4 for each manufacturer tested. There is no statistically significant difference between configurations #1 and #3 and #2 and #4, respectively ($P < .001$) (Table 2). Note the distinct difference between configurations #1 and #3 versus #2 and #4

TABLE 2 Initial forces for chain configurations #1-#4 and chain type (closed/open) (N = 20)

		Force averaged over all gap widths (N) – Median [min.; max.]								Kruskal-Wallis	
Manufacturer	Chain type	#1 BOBOBOB		#2 BOBBOB		#3 BBOBB		#4 BBBB		*P*	Sub groups
AO	Closed	5.2	[1.4; 7.7]	9.4	[0.1; 16.6]	5.7	[2.5; 8.4]	10.9	[4.5; 19.7]	<.001	1/3:2/4 (1/3:2/3:2/4)
	Open	3.0	[0.1; 5.6]	7.8	[3.6; 11.6]	3.9	[0.2; 6.1]	7.9	[3.1; 13.7]	<.001	1/3:2/4
Forestadent	Closed	3.7	[1.1; 6.4]	5.7	[1.7; 13.1]	3.6	[1.4; 6.1]	8.3	[4.0; 13.7]	<.001	1/3:2/4 (1/3:2/3:1/2:2/4)
	Open	2.2	[0.1; 4.2]	5.9	[2.0; 10.5]	2.2	[0.2; 4.1]	6.2	[2.4; 10.1]	<.001	1/3:2/4
Ormco	Closed	3.7	[1.1; 6.3]	9.0	[3.7; 13.3]	3.9	[1.7; 6.4]	9.9	[5.3; 14.3]	<.001	1/3:2/4
	Open	2.3	[0.2; 4.1]	6.7	[2.7; 10.8]	2.5	[0.7; 4.8]	7.3	[3.1; 10.9]	<.001	1/3:2/4
RMO	Closed	3.4	[1.1; 5.9]	8.7	[3.1; 13.2]	3.9	[1.5; 6.2]	9.0	[4.4; 13.5]	<.001	1/3:2/4
	Open	1.7	[0.1; 3.5]	4.8	[1.9; 8.1]	1.8	[0.1; 3.3]	4.8	[2.0; 8.5]	<.001	1/3:2/4

Note: Sub-groups organized after group-wise comparisons; changes due to Bonferroni correction were given in braces. Configurations #1-#4: B stands for elastic ring with bracket, while O designates elastic ring without bracket.

significantly higher than for open chains regardless of manufacturer, chain configuration or gap width ($P = .029$).

3.3 | Configuration #3 (B-B-O-B-B)

Depending on the manufacturer, the initial forces of the closed chains at a gap of 8 mm varied between 5.6 and 8.2 N. Given a gap width of 4 mm the forces acting on the teeth were between 3.6 and 5.7 N. With a residual gap width of 0.5 mm forces of 1.5-2.6 N still acted on the teeth.

The initial forces of the open chains at a gap width of 8 mm ranged between 3.2 and 6.0 N, depending on the manufacturer. With a gap width of 4 mm the forces acting on the teeth were between 1.8 and 3.9 N. With a gap width of 0.5 mm, forces of 0.1-0.9 N still acted on the teeth.

A significant difference in initial forces between the closed chains of the different manufacturers was observed (Table 3, Figure 3). With open chains, similar observations were made (Table 3, Figure 3), especially at gap widths of 2.0, 4.0 and 6.0 mm.

3.4 | Configuration #4 (B-B-B-B)

The initial forces of the closed chains at a gap width of 8 mm were between 13.0 and 19.0 N, depending on the manufacturer. Given a gap width of 4 mm, the forces acting on the teeth were between 8.3 and 10.9 N. With a gap width of 0.5 mm, forces of 4.0-5.6 N were still acting on the teeth.

The initial forces of the open chains at a gap width of 8 mm were between 8.1 and 12.9 N, depending on the manufacturer. At a gap width of 4 mm, the forces acting on the teeth were between 4.8 and 8.1 N. Shortly before the gap is completely closed (gap width of 0.5 mm), forces of 2.3-4.0 N were still acting on the teeth.

A significant difference in forces delivered between the closed and open chains of the different manufacturers were observed (Table 3, Figure 3).

4 | DISCUSSION

According to this study, closed elastic power chains delivered significantly higher forces than open chains independent of the manufacturer. Comparing the forces exerted by elastic chains during gap closure, the results of this study showed differences up to 5 N, depending on the manufacturer of the chain. The four configurations tested differed in the presence and position of intermediate chain rings. Additional intermediate chain rings between the teeth adjacent to the gap were not required to modulate force during gap closure. On the other hand, leaving an elastic ring unapplied in the tooth gap can help modulate the force.

Earlier studies have shown that even small forces (0.25 N) are sufficient for orthodontic tooth movement and only lead to a low degree of hyalinization.[12–17] Only moderate forces should be considered during gap closure to avoid indirect resorption and jiggling.[18–20] In addition to the force magnitude, frictional forces between wire and slot also play an important role in sliding mechanics. Friction and binding depend on various factors such as bracket material and bracket slot geometry, archwire size and material, material surface characteristics, lubrication, applied force, inter-bracket distance, and wire-bracket angle.[21–27] In order to isolate the initial forces produced by orthodontic elastic chains

TABLE 3 Forces [N] of closed and open orthodontic chains in configurations #3 and #4 at different gap distances

			Force (N)												Kruskal-Wallis	
			AO			Forestadent			Ormco			RMO				
Chain type	Chain configuration	Tooth gap (mm)	Median	Min	Max	Median	Min	Max	Median	Min	Max	Median	Min	Max	*P* value	Subgroups
Closed	#3 BBOBB	0.5	2.6^{bX}	2.5	2.7	1.5^{bX}	1.4	1.6	2.0^{bX}	1.7	2.2	1.7^{bX}	1.5	2.0	.006	F/R/O:A
		2.0	4.3^{bX}	4.0	4.5	2.7^{bX}	2.5	2.8	3.0^{bX}	2.8	3.1	2.8^{bX}	2.4	3.1	.016	F/R/O:A
		4.0	5.7^{bX}	5.4	6.0	3.6^{bX}	3.4	3.9	3.9^{bX}	3.7	4.1	3.9^{bX}	3.3	4.3	.024	F/R/O:A
		6.0	6.9^{bX}	6.8	7.2	4.6^{bX}	4.3	4.9	4.9^{bX}	4.5	5.1	4.9^{bX}	4.3	5.2	.026	F/R/O:A
		8.0	8.2^{bX}	8.0	8.4	5.6^{bX}	5.1	6.1	5.9^{bX}	5.4	6.4	5.8^{bX}	5.5	6.2	.031	F/R/O:A
	#4 BBBB	0.5	5.1^{aX}	4.5	5.3	4.0^{aX}	4.0	4.1	5.6^{aX}	5.3	5.7	4.6^{aX}	4.4	5.0	.005	F/R:A/O
		2.0	7.3^{aX}	6.3	8.2	6.0^{aX}	5.7	6.2	7.6^{aX}	7.3	7.9	6.6^{aX}	6.3	7.0	.009	F/R:R/A/O:A/O
		4.0	10.9^{aX}	9.4	12.1	8.3^{aX}	8.0	8.5	9.9^{aX}	9.6	10.0	9.0^{aX}	8.7	9.1	.005	F/R:R/O:A/O
		6.0	14.9^{aX}	13.6	15.8	10.8^{aX}	10.5	11.1	12.0^{aX}	11.7	12.1	10.9^{aX}	10.8	11.3	.005	F/R:R/O:A/O
		8.0	19.0^{aX}	17.9	19.7	13.3^{aX}	12.7	13.7	14.1^{aX}	13.8	14.3	13.0^{aX}	12.7	13.5	.005	F/R/O:A
Open	#3 BBOBB	0.5	0.5^{bY}	0.2	1.1	0.4^{bY}	0.2	0.6	0.9^{bY}	0.7	1.1	0.1^{bY}	0.1	0.3	.007	F/R/O:A/O
		2.0	2.6^{bY}	2.4	2.8	1.4^{bY}	1.2	1.6	1.8^{bY}	1.7	1.8	0.9^{bY}	0.7	1.1	.004	F/R:F/O:A/O
		4.0	3.9^{bY}	3.8	4.1	2.2^{bY}	2.0	2.4	2.5^{bY}	2.3	2.7	1.8^{bY}	1.7	2.0	.004	F/R:F/O:A/O
		6.0	5.0^{bY}	4.9	5.1	3.0^{bY}	2.7	3.2	3.2^{bY}	2.9	3.7	2.4^{bY}	2.4	2.7	.004	F/R:F/O:A/O
		8.0	6.0^{bY}	5.9	6.1	3.8^{bY}	3.4	4.1	4.0^{bY}	3.7	4.8	3.2^{bY}	3.0	3.3	.005	F/R/O:A
	#4 BBBB	0.5	4.0^{aY}	3.1	4.5	3.0^{aY}	2.4	3.0	3.7^{aY}	3.1	4.0	2.3^{aY}	2.0	2.7	.019	F/R/O:A
		2.0	5.9^{aX}	4.5	6.3	4.5^{aY}	3.7	4.5	5.4^{aY}	4.3	5.8	3.4^{aY}	2.7	4.0	.003	F/R:F/O:A/O
		4.0	8.1^{aY}	6.2	8.7	6.2^{aY}	5.3	6.3	7.3^{aY}	6.1	7.7	4.8^{aY}	3.8	5.6	.004	F/R:F/O:A/O
		6.0	10.5^{aY}	8.3	11.2	7.9^{aY}	7.1	8.2	9.0^{aY}	7.8	9.2	6.5^{aY}	5.3	6.9	.005	F/R:F/O:A/O
		8.0	12.9^{aY}	11.0	13.7	9.7^{aY}	8.9	10.1	10.7^{aY}	9.6	10.9	8.1^{aY}	7.1	8.5	.005	F/R:F/O:A/O

Note: For each combination of chain type, chain configuration and manufacturer four (N = 4) chains were tested. Kruskal-Wallis tests were carried out as described. Homogenous subgroups were determined by multiple-comparisons with Bonferroni correction applied. These subgroups are named using the first letter of the suppliers name, for example, F stands for Forestadent, while R stands for RMO. Mann-Whitney U tests were carried out as described. "a/b" designates differences between chain configurations (#3 vs. #4) for each manufacturer/gap width/chain type combination. Values with X, Y are statistically different when comparing chain type (open vs. closed) for each manufacturer/chain configuration/gap width combination.

during a simulated gap closure, no archwires were incorporated in the experimental setup. Assuming a frictional force of 1-1.5 N, the force generated by the chains during gap closure should not exceed 1.5-2 N.[28–33] Thus, the actual force load per tooth is reduced to approximately 0.5 N, which is suitable for physiological tooth movement.[13,34]

In view of these considerations, our measurements indicated that it is necessary to switch between different chain configurations and different manufacturers in order to achieve an initial force level between 1.5 and 2 N. Taking into account a relative force decay of 20%-25% for thermoset chains and 40%-50% for thermoplastic chains within the first hour after application,[4,5] the following recommendations can be made based on our results: for gap widths <2 mm, open thermoset chains (RMO) and closed thermoplastic chains (Forestadent) produced suitable initial forces (configuration #4). For gap widths >2 mm and <4 mm, open thermoset chains (Ormco) can be employed (configuration #3). For gap widths >4 mm, forces of chains in the tested configurations were mostly too high (Table 3), although open thermoplastic chains (Forestadent, #3) and open thermoset chains (RMO, #3) still produced acceptable forces at a gap width of 6 mm. Considering the difficulty of clinically controlling forces and possible adverse effects, the use of segmented archwires, retraction archwires or NiTi coil springs should be considered for the closure of large gaps.[35,36]

Orthodontic space closure is commonly performed using sliding mechanics or closing loops, with sliding mechanics representing the predominant method.[31,33,37] Although NiTi coil springs provide relatively constant force levels and have been found to close gaps faster, or at least at a similar rate, orthodontic elastic chains are widely used being the cheaper alternative.[31,33] Orthodontic tooth movement is determined by the moment-to-force (M/F) ratio.[2] Therefore, when using elastic chains, a controlled and differentiated force application is necessary to avoid an unfavourable M/F ratio. The use of excessive force can cause adverse effects such as tooth tipping, increased hyalinization and root resorption.[8] In contrast, frictionless mechanics with closing loops allow the application of defined forces and moments, but bending and readjustment are significantly more complex and the mechanics can irritate the soft tissue.[33]

As the comparability of the different gap distances was the main concern in this study, the elastic chains were pre-stretched to the full 8.0 mm initially. This corresponds to the maximum simulated gap of the gap closure. The effect of pre-straining remains controversial, sometimes it is recommended to do so while others negate a positive effect.[4,38] Still, as all chains received the same level of pre-strain, the alteration in the force level can be assumed equal.

Initially, the final step of gap closure (i.e. gap width of 0 mm) was included in our simulation, but the force measurements showed a large variability and were not reproducible. We observed that this gap was too small in comparison to the dimensions of an elastic chain with inter-modular links. Thus, these chains were no longer stretched but instead bent at an angle of approximately 30-60°. We suppose, that this bending and squeezing resulted in additional, uncontrollable pressure onto the brackets, leading to inaccurate measurements. Consequently, we decided to measure forces up to a remaining gap width of 0.5 mm. This is similar to the clinical situation, in which an elastic chain without inter-modular links is selected for the final stages of gap closure.

An idealized situation with a mobile plate was created in the present study. The brackets 2 and 6 served for illustration purposes and to test the effect of an extra intermediate ring when physiological inter-proximal distances are present. It was not meant to show the simultaneous retraction of the canine and lateral incisor. This is important when interpreting the clinical relevance of the forces generated with the elastic configurations. Morphological differences of the chains investigated have not been taken into account in the present study. Clinically, however, it is also the case that practitioners cannot configure the morphology of elastic chains and must choose from products available on the market. In particular, choosing between different material classes (thermoset [TSU]/thermoplastic [TPU]) and using additional inter-modular links are useful possibilities to control the force during orthodontic gap closure of different distances. Therefore, we evaluated four commonly used elastomeric chains from different manufacturers and derived possible clinical protocols to produce suitable forces.

To conclude, suitable initial forces at different gap widths could not be achieved with chains from the same manufacturer according to our measurements, even when intermediate rings were used to modulate the force. Therefore, force measurements with a gauge are clinically recommended, or chains from different manufacturers should be selectively varied.

In addition, the differences in force decay of either thermoset or thermoplastic chains should be considered. With thermoplastic chains, the force decreases much faster over time.[5] Therefore, these chains should be replaced within shorter intervals. In our study, chains made from thermoplastic polyurethane tend to have higher initial forces than chains made from thermoset polyurethane.

5 | CONCLUSION

Additional intermediate chain rings between teeth adjacent to the gap are not required to modulate the force released by the elastic chains during gap closure. But, leaving a ring unapplied within the gap modulates the force release of the chain.

Elastic chains in the tested configurations do not appear suitable for a gap closure of >4 mm, as the measured forces were mostly too high, even if a force decay of 20%-40% is taken into account. Therefore, the use of segmented archwires, retraction archwires or NiTi coil springs should be considered for the closure of gaps > 4 mm.

For a gap closure of 4 mm, open thermoset chains with an additional ring within the gap (configuration #3) produced suitable initial forces.

With a residual gap < 2 mm, configuration #4 appears to be more suitable, as the forces with configuration #3 become too small. Closed thermoset chains and open thermoplastic chains show an adequate initial force at a gap width of 0.5 mm.

In summary, initial forces of elastic chains for gap closure in sliding mechanics appear to be suitable for gap widths up to 4 mm, although the application of different chain configurations must be considered. Force measurements with a gauge are clinically recommended in order to control the force application of elastic chains.

AUTHOR CONTRIBUTIONS

H.S. writing - original draft preparation, data interpretation and synthesis. E.B. writing - original draft preparation. A.K. methodology and experiments. T.S. methodology and experiments. U.B. statistical analysis and data interpretation. L.H. writing - review. A.W. conceptualization, project administration and supervision. All authors have read and agreed to the published version of the manuscript.

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CONFLICT OF INTEREST

The authors have nothing to disclose.

DATA AVAILABILITY STATEMENT

The full datasets of the study can be provided upon reasonable request through the corresponding author.

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