

# Innovative design of closing loops producing an optimal force system applicable in the 0.022-in bracket slot system

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**Introduction:** Most closing loops designed for producing higher moment-to-force (M/F) ratios require complex wire bending and are likely to cause hygiene problems and discomfort because of their complicated configurations. We aimed to develop a simple loop design that can produce optimal force and M/F ratio.

**Methods:** A loop design that can generate a high M/F ratio and the ideal force level was investigated by varying the portion and length of the cross-sectional reduction of a teardrop loop and the loop position. The forces and moments acting on closing loops were calculated using structural analysis based on the tangent stiffness method.

**Results:** An M/F ratio of 9.3 (high enough to achieve controlled movement of the anterior teeth) and an optimal force level of approximately 250 g of force can be generated by activation of a 10-mm-high teardrop loop whose cross-section of  $0.019 \times 0.025$  or  $0.021 \times 0.025$  in was reduced in thickness by 50% for a distance of 3 mm from the apex, located between a quarter and a third of the interbracket distance from the canine bracket.

**Conclusions:** The simple loop design that we developed delivers an optimal force and an M/F ratio for the retraction of anterior teeth, and is applicable in a 0.022-in slot system. (*Am J Orthod Dentofacial Orthop* 2016;150:968-78)

There are 2 mainstream methods of space closure in orthodontic treatment after tooth extractions.<sup>1,2</sup> One is the friction technique, which consists of sliding mechanics wherein a straight archwire slides through the brackets and tubes on the posterior teeth.<sup>3-6</sup> The other is the frictionless technique, which

consists of loop mechanics wherein space closure is achieved by activating closing loops incorporated into an archwire.<sup>7-17</sup> Because the demand for shortening the treatment period and simplifying the process of archwire bending increases, en-masse retraction with sliding mechanics have more frequently been performed, especially in recent years with the combined use of temporary anchorage devices for improving therapeutic efficiency in orthodontic treatment.<sup>2,4,5</sup> Most clinicians who practice sliding mechanics use the 0.022-in slot system because a larger and more rigid archwire is required to prevent undesirable bowing effects during space closure.<sup>3</sup> In sliding mechanics, however, friction is developed at the bracket-wire interface; this may decrease the rate of tooth movement during space closure.<sup>3,6</sup>

All of the retraction force generated by loops can be directly transmitted to the anterior teeth from the archwire in loop mechanics because of its frictionless mechanism, unlike in sliding mechanics. Therefore, this technique has the potential to produce predetermined moment-to-force (M/F) ratios to accurately achieve controlled movement of the anterior teeth.<sup>18-21</sup> From the perspective of biomechanics, loop mechanics are still considered a much more efficient technique for

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achieving the desired type of tooth movement in a predictable manner.

However, a shortcoming of loop mechanics is that the M/F ratio produced by conventionally designed loops made of stainless steel wire is too low to achieve controlled tipping or translation of the anterior tooth.<sup>18</sup> To increase the M/F ratio, several designs of loops in complicated shapes with low load-deflection rates have been fabricated.<sup>7-17</sup> When the load-deflection rate of the loop is lowered so that the retraction force is decreased, the M/F ratio can be raised because the decrease in the force magnitude is greater than the decrease in the amount of moment.<sup>18-21</sup>

Another method used to raise the M/F ratio is to place a gable bend in the closing loop. However, a gable bend in a loop could produce an excessively heavy force.<sup>21-24</sup> Moreover, the use of an archwire with a larger cross-section could generate a greater retraction force in the case of the 0.022-in slot system. Profit<sup>18</sup> reported that an 8-mm vertical loop in an  $0.018 \times 0.025$ -in stainless steel wire produces a retraction force of 500 g per millimeter, which is twice as much as the desired force magnitude for retraction of the anterior teeth. For this reason, most clinicians who practice loop mechanics use the 0.018-in slot system nowadays. If, however, it is desired to use loop mechanics in the 0.022-in slot system, there is a need for an innovative design of a closing loop generating a lighter force and a higher M/F ratio, whose values range from 7 for controlled tipping to 10 for translation of the anterior teeth.<sup>20,25</sup>

The purpose of this study was to use structural analysis to develop a simple design for a loop that can produce a higher M/F ratio and a gentler force without the addition of gable bends and also improve patient comfort with the 0.022-in slot system.

## MATERIAL AND METHODS

The forces and moments acting on the ends of the closing loops were determined using a computer program for geometric nonlinear analysis based on the tangent stiffness method, by which large deflections can be handled.<sup>26</sup> This structural analysis has thus enabled determination of the force system generated by closing loops more accurately than the finite element method, which is valid only for small deflections. The basic design of the closing loop examined in this study was a teardrop, 10 mm in height. The interbracket distance was 10 mm, and the loop was bent from  $0.019 \times 0.025$ -in or  $0.021 \times 0.025$ -in stainless steel wire with Young's modulus of 200,000 MPa. The teardrop loop configuration was idealized by 62 elements. Assuming that the loop is activated by 1 mm, analysis

of the loop is performed by giving forced displacements of 1.0 mm to both ends. Forces and moments acting on both ends of the loop were calculated upon each application of the above-mentioned boundary conditions.

In the first step, the rectangular cross-section of the wire was partially reduced by 30% in both thickness (shorter side) and width (longer side) in different regions (1/3 from the apex of the loop, 1/3 in the middle, and 1/3 from the base) (Fig 1). We calculated the force system produced by the loops and determined which loop design produced the highest M/F ratio. The loops were bent from  $0.019 \times 0.025$ -in stainless steel wire and set at a third of the interbracket distance from the canine bracket.

In the second step, forces and moments generated at the loop ends with the partial reduction in the wire cross-section (30% reduction in thickness and width) for 0, 1, 2, 3, 4, and 5 mm from the loop apex were respectively calculated to determine the optimal length of cross-sectional reduction from the apex of the loop fabricated of  $0.019 \times 0.025$ -in wire to produce the highest M/F ratio. The loops were placed at a third of the interbracket distance from the canine bracket.

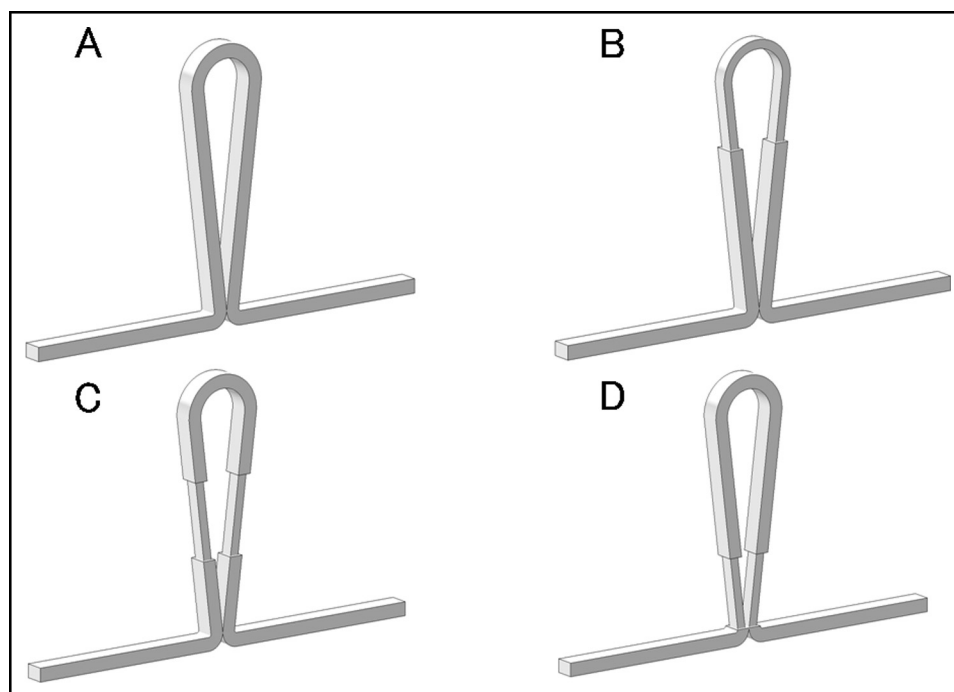
In the third step, the mechanical characteristics of 2 closing loops bent from  $0.019 \times 0.025$ -in or  $0.021 \times 0.025$ -in wire, in which either the thickness or the width of the cross-section was reduced, associated with various reductions in the wire size by 0%, 10%, 20%, 30%, 40%, or 50%, were analyzed when the loops were placed at a third of the interbracket distance from the canine bracket (Fig 2). The reduced portion extended 3 mm from the apex of the loop. Then, the combination of the site and the rate of reduction in the wire cross-section that produced the highest M/F ratio was determined.

In the fourth step, the forces and moments generated at the loop ends at varying loop positions (1/10, 1/5, 1/4, 1/3, or 1/2 [center] of the interbracket distance from the canine bracket) were calculated to investigate the optimal loop position that generated the highest M/F ratio (Fig 3). In this analysis, 2 wire sizes ( $0.019 \times 0.025$  and  $0.021 \times 0.025$  in) were used, and the values of force, moment, and M/F ratio were compared.

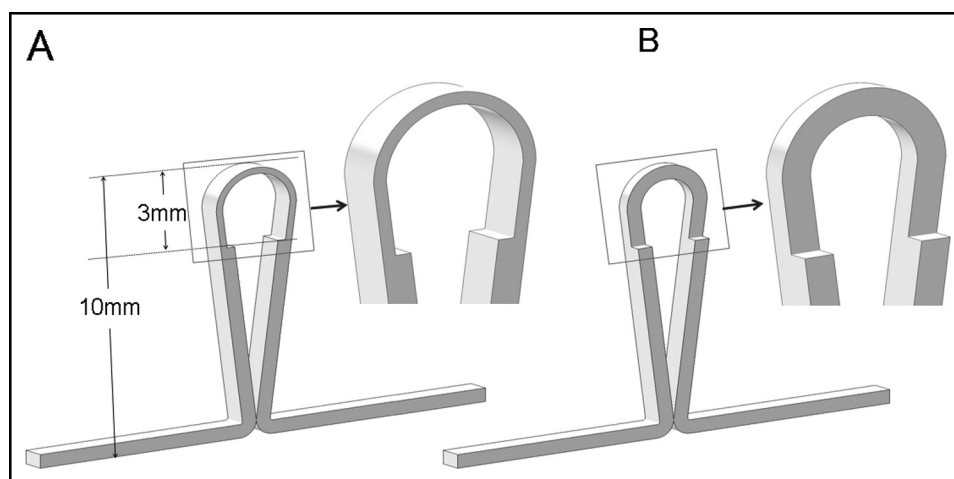
## RESULTS

### Effect of the region of cross-sectional reduction of the loop on the force system

Figure 4 shows the forces, moments, and M/F ratios acting on the ends of the closing loop (10 mm high with a cross-section of  $0.019 \times 0.025$  in), with an activation of 1 mm. When the apical third of the loop was reduced in cross-section (Fig 4, B), the force



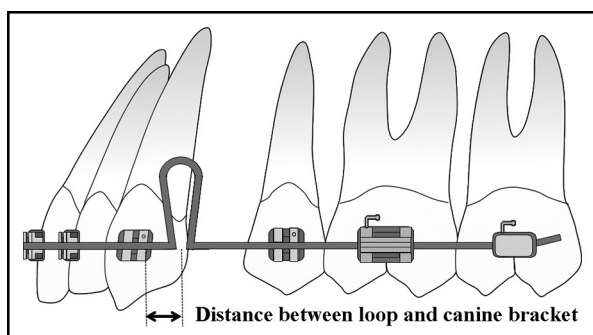
**Fig 1.** Variations in the region of cross-sectional reduction of the wire in an occlusogingival direction (30% reduction in both thickness and width of the loop): **A**, no reduction; **B**, reduction in the apical (gingival) third of the loop; **C**, reduction in the middle third of the loop; **D**, reduction in the basal (occlusal) third of the loop.



**Fig 2.** Two patterns of reduction in the wire cross-section: **A**, reduction in thickness of the wire cross-section for a distance of 3 mm from the loop apex; **B**, reduction in width of the wire cross-section for a distance of 3 mm from the loop apex.

magnitude was markedly reduced from 357 to 182 g of force. When the cross-section of the middle portion (Fig 4, C) and the basal portion (Fig 4, D) were reduced, forces of 325 and 271 g of force were respectively produced, and the reduction rate of the force

was much lower than in Figure 4, B, in which the cross-section of the apical portion of the loop was reduced. The smallest decrease in moment was observed in Figure 4, C (from 2019 to 2065 g of force per mm), followed by Figure 4, B (from 2019 to



**Fig 3.** Schematic representation of the loop position indicating a distance from the canine bracket to the center of the loop.

1570 g of force per mm), and with the greatest decrease in [Figure 4, D](#) (from 2019 to 1115 g of force per mm).

The M/F ratio was substantially increased from 5.8 to 8.6 in [Figure 4, B](#), in which the apical third of the loop was reduced in cross-section. Although the M/F ratio increased to 6.4 in [Figure 4, C](#), the amount of the increase was smaller than for [Figure 4, B](#). By contrast, the M/F ratio decreased to 4.1 in [Figure 4, D](#).

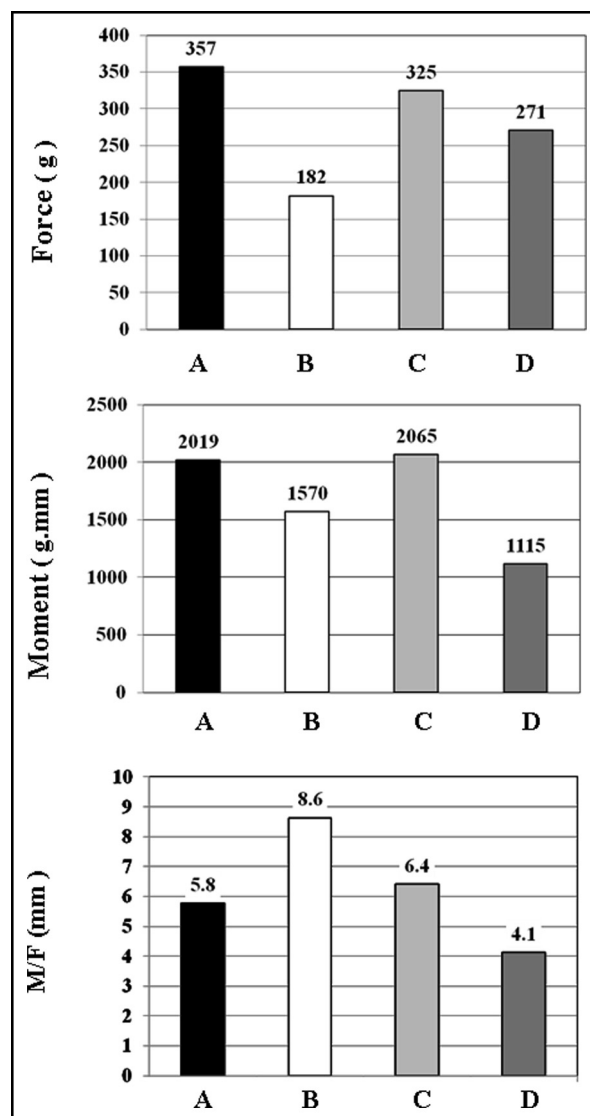
#### Effect of the cross-sectional reduction in length from the loop apex on the force system

[Figure 5](#) shows forces, moments, and M/F ratios acting on the ends of closing loop, whose original cross-section is  $0.019 \times 0.025$  in, when varying the length of partial reduction in cross-section from the loop apex by 1, 2, 3, 4, and 5 mm. With the reduction of 1, 2, 3, 4, and 5 mm, the force was decreased from 357 g (for no wire-size reduction) to 197, 185, 182, 181, and 179 g, respectively. Thus, the force decreased as the length of cross-sectional reduction from the apex of the loop was increased.

On the other hand, the decrease in moment was less remarkable, up to 4 mm of cross-sectional reduction of the loop, when compared with the decrease in force. The moment was substantially decreased from 2019 to 1502 g of force per mm with a partial reduction of 5 mm. A cross-sectional reduction of 3 mm from the tip of the loop produced the greatest M/F ratio of 8.63, followed by 8.57 for 4 mm, 8.49 for 2 mm, 8.38 for 5 mm, and 8.01 for 1 mm reductions.

#### Effect of the cross-sectional reduction of the loop by either thickness or width on the force system

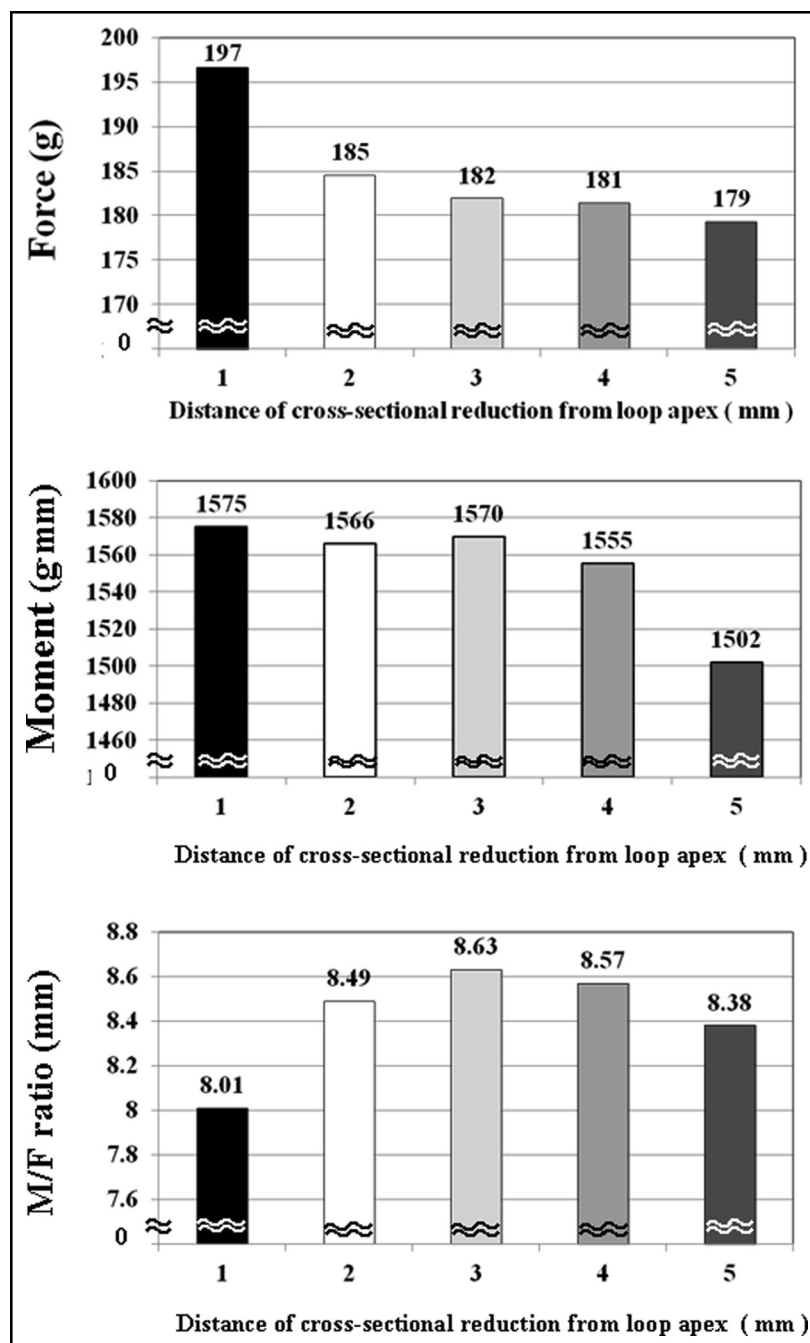
[Figure 6](#) shows the forces, moments, and M/F ratios acting on the ends of the closing loop, whose cross-section thickness or width was reduced by 3 mm from



**Fig 4.** Effect on mechanical properties of a 30% reduction in both thickness and width of the wire cross-section in various areas of the  $0.019 \times 0.025$ -in teardrop loop: A, No reduction; B, reduction in the apical third of the loop; C, reduction in the middle third of the loop; D, reduction in the basal third of the loop.

the apex, when varying the reduction rate from 0% to 50% at an interval of 10%. Closing loops bent from  $0.019 \times 0.025$ -in wire ([Fig 6, A](#)) and  $0.021 \times 0.025$ -in wire ([Fig 6, B](#)) were tested.

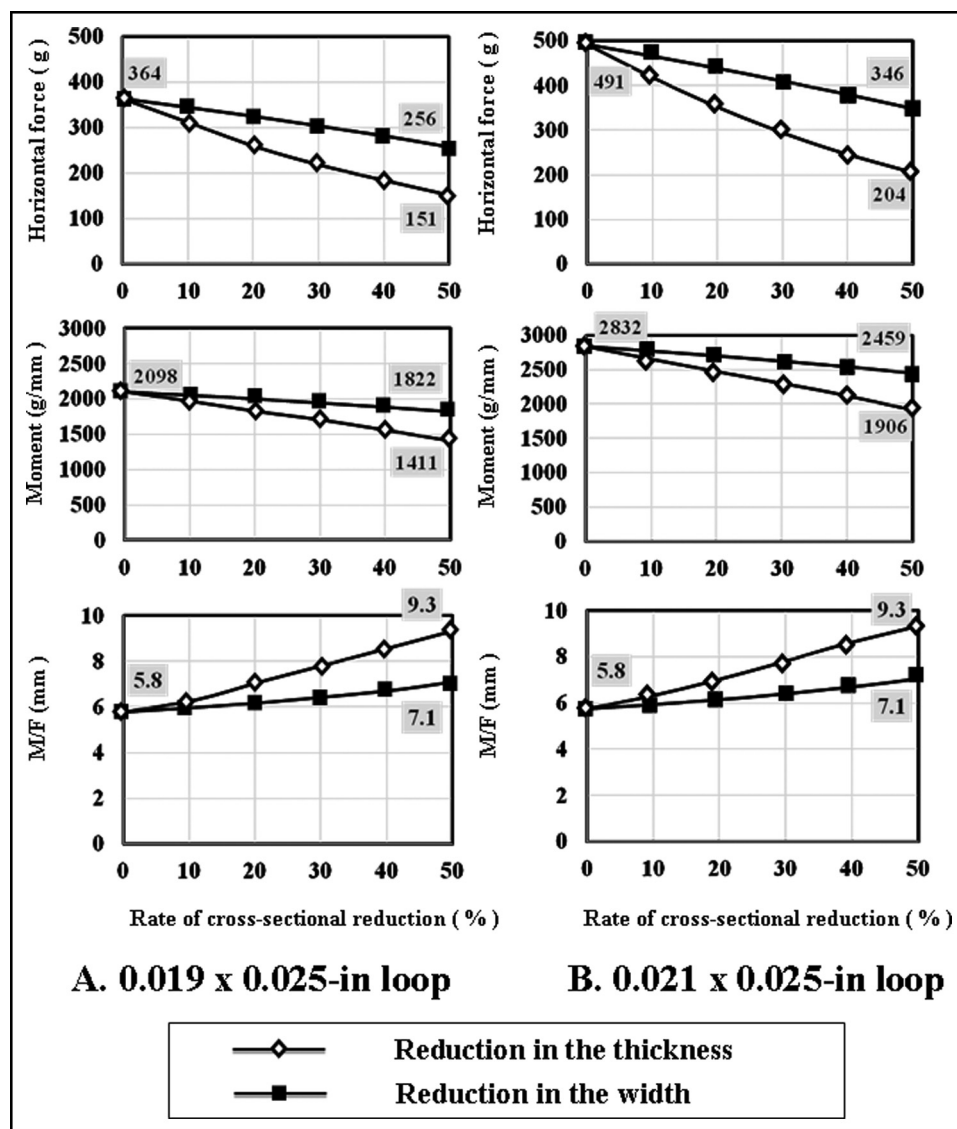
As the reduction rate of the wire cross-section of the  $0.019 \times 0.025$ -in loop was increased from 0% to 50%, the force magnitude was decreased from 364 to 151 g with a reduction in wire thickness, and from 364 to 256 g with a reduction in wire width. For the  $0.021 \times 0.025$ -in closing loop, the force was decreased



**Fig 5.** Effect on mechanical properties of a 30% reduction in both thickness and width of the wire cross-section of a  $0.019 \times 0.025$ -in loop at varying distances of the cross-sectional reduction from the loop apex from 1 to 5 mm at an interval of 1 mm.

from 491 to 204 g with a reduction in wire thickness, and from 491 to 346 g with a reduction in wire width. A similar tendency was observed for the moment. Thus, the moment decreased with an increased reduction rate of the wire cross-section by either thickness or width.

However, the decreasing rate of force was much higher than that of the moment. The magnitudes of force and moment generated with the  $0.019 \times 0.025$ -in loop were lower compared with the  $0.021 \times 0.025$ -in loop at every rate of the wire-size reduction at both sides.



**Fig 6.** Forces, moments, and M/F ratios generated by 2 closing loops bent from: **A**,  $0.019 \times 0.025$ -in and **B**,  $0.021 \times 0.025$ -in wire, in which either the thickness or the width of the cross-section was reduced for a distance of 3 mm from the loop apex, associated with various reduction rates of the wire size by 0%, 10%, 20%, 30%, 40%, and 50%.

Conversely, the M/F ratio was increased from 5.8 to 9.3 with a reduction in thickness, and from 5.8 to 7.1 with a reduction in width of the wire cross-section when raising the reduction rate of the wire cross-section from 0% to 50%. The M/F ratio was increased by 1.6 times when the thickness of the loop was reduced by 50%, and by 1.2 times when the width was reduced by 50% (Table). The values of the M/F ratio for the  $0.019 \times 0.025$ -in closing loop were similar to those for the  $0.021 \times 0.025$ -in closing loop.

#### Effect of loop position on the force system

Figure 7 shows the forces, moments, and M/F ratios acting on the ends of a closing loop, whose cross-section thickness was reduced by 0% (without reduction) or by 50% in the region 3 mm from the apex of the loop by varying the loop position at 1/10, 1/5, 1/4, 1/3, and 1/2 (center) of the interbracket distance from the canine bracket. Closing loops bent from  $0.019 \times 0.025$ -in (Fig 7, A) and  $0.021 \times 0.025$ -in (Fig 7, B) wires were analyzed.



**Table.** Comparison of forces, moments, and M/F ratios produced by 0.019 × 0.025-in and 0.021 × 0.025-in closing loops when reducing the thickness and the width

	Rate of reduction in thickness (%)		Rate of reduction in width (%)	
	0	50	0	50
0.019 × 0.025-in closing loop				
Force (g)	364	151	364	256
Moment (g mm)	2098	1411	2098	1822
M/F	5.8	9.3	5.8	7.1
Relative value of M/F ratio (times)*	1	1.6	1	1.2
0.021 × 0.025-in closing loop				
Force (g)	491	204	491	346
Moment (g mm)	2832	1906	2832	2459
M/F	5.8	9.3	5.8	7.1
Relative value of M/F ratio (times)*	1	1.6	1	1.2

\*Relative value of M/F ratio wherein 1 is taken for the value without reduction of wire cross-section.

As the closing loop was displaced in the distal direction from the canine bracket toward the center of the interbracket distance, the magnitudes of force and moment were decreased in the 0.019 × 0.025-in and 0.021 × 0.025-in loops regardless of whether the wire cross-section was reduced. In other words, the closer the loop was placed to the canine bracket, the greater the force and moment generated.

However, the M/F ratio increased when the loop was moved from the canine bracket toward a point a quarter of the interbracket distance from the canine bracket for both the 0.019 × 0.025-in and 0.021 × 0.025-in loops regardless of whether the wire cross-section was reduced. When the loop was placed between a quarter and a third of the interbracket distance, maximum M/F ratios of 5.9 and 9.3 were observed with reduction of wire cross-section in the thickness by 0% and 50%, respectively. The M/F ratio was decreased when the loop was moved farther distally from a point a third toward half (center) of the interbracket distance. There was no significant difference in the M/F ratio between the 0.019 × 0.025-in and 0.021 × 0.025-in loops at any corresponding loop position.

## DISCUSSION

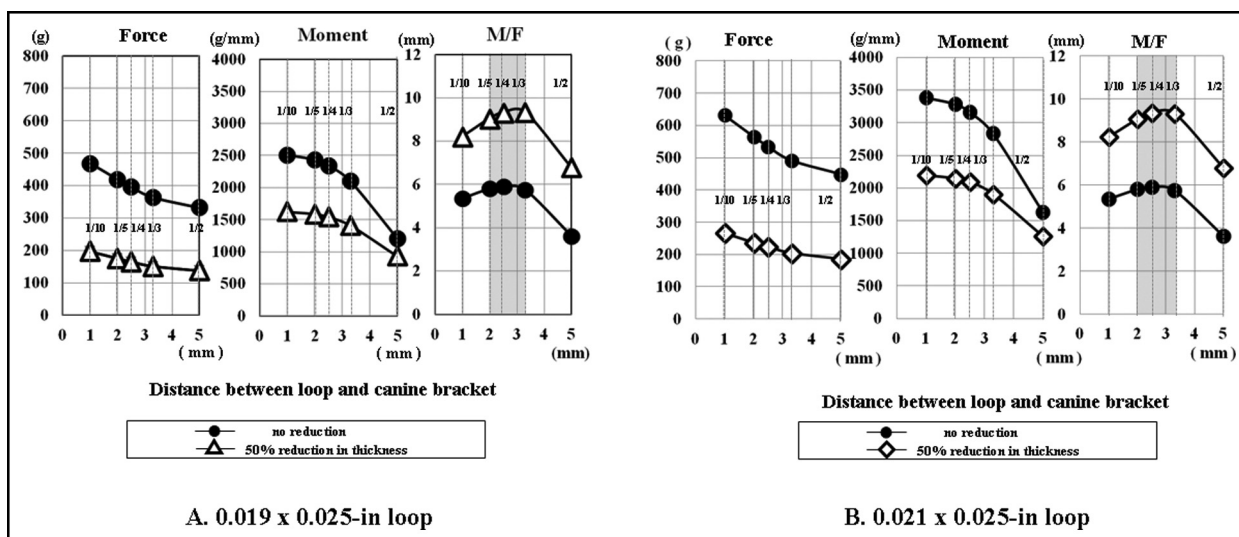
Two types of mechanics have been commonly used for space closure after extractions.<sup>1,2</sup> One is sliding mechanics, in which a plain archwire slides through the brackets and tubes on the posterior teeth.<sup>3-6</sup> The other is loop mechanics, in which space closure is

achieved by activation of closing loops incorporated into an archwire.<sup>7-17</sup>

Although sliding mechanics are quite advantageous in regard to reducing the amount of wire bending, which leads to simplified mechanics and improved patient comfort and oral hygiene, a great amount of friction could inhibit tooth movement during space closure.<sup>3</sup> Additionally, the force and moment acting on each tooth cannot be easily determined because of the friction generated. Hence, it is difficult to precisely predict how a tooth will move in a preprogrammed direction (eg, controlled tipping, bodily movement, or root movement) during orthodontic treatment.<sup>3,6</sup>

Such an unpredictable loss of force is never incurred in loop mechanics because it is frictionless. This technique has, therefore, the potential to produce optimal M/F ratios for accurately achieving controlled movement of the anterior teeth predictably.<sup>18-21</sup> However, the M/F ratio generated by the conventional vertical or teardrop loop is too low to achieve controlled movement of the anterior teeth.<sup>8,10,16-18,21,23</sup> The M/F ratio is the most important mechanical characteristic of the loop because it determines the center of rotation and thus the movement pattern of the tooth during space closure.<sup>18-21,25</sup> Burstone and Koenig<sup>21</sup> reported that the vertical height of the loop is the dominant factor influencing the M/F ratio, and the higher the loop, the greater the M/F ratio. Our study showed that an M/F ratio of 5.8 was generated when the height of a teardrop loop bent from 0.019 × 0.025-in stainless steel wire was 10 mm (Fig 4). Previous studies have reported that an M/F ratio of 5 to 7 is required to achieve controlled tipping, 10 for bodily movement, and 12 for root movement.<sup>20,25</sup> According to these requirements, bodily movement or root movement cannot be achieved even with a 10-mm-high teardrop loop, although controlled tipping could be attained.

To generate a higher M/F ratio, many loop designs with complicated shapes have been developed by extending the horizontal length as well as the vertical height.<sup>7-17</sup> To cite an example, Burstone and Koenig<sup>21</sup> designed a T-loop, evaluated its mechanical characteristics, and found that T-loops produce a higher M/F ratio than do vertical loops with the same height. Siatkowski<sup>16,17</sup> developed the Opus loop, which can deliver an M/F ratio of 8.0 to 9.1, by incorporating a helix into an L-loop with a vertical height and horizontal length of 10 mm each. Despite every possible effort to design loops producing the optimal force system in the previous studies, the M/F ratio generated by the T-loop or the Opus loop can never be higher than the vertical height of the loop, even if the horizontal length and vertical height are increased. Additionally, such attempts to raise the M/F ratio may



**Fig 7.** Effect of the loop position at various distances from the canine bracket on the mechanical properties of  $0.019 \times 0.025$ -in and  $0.021 \times 0.025$ -in loops with and without a 50% reduction in the thickness of the wire cross-section for a distance of 3 mm from the loop apex: **A**,  $0.019 \times 0.025$ -in teardrop loop with and without cross-sectional reduction of the wire; **B**,  $0.021 \times 0.025$ -in teardrop loop with and without cross-sectional reduction of the wire.

cause hygiene problems, irritation, and discomfort.<sup>16-19</sup> Another method for increasing the M/F ratio is to incorporate gable bends into closing loops. However, the greater the angle of the gable bend that is incorporated, the heavier the force produced—beyond what clinicians might expect.<sup>21-24</sup> Moreover, the amount of retraction force will increase further when an archwire with a larger cross-section is used in the 0.022-in slot system rather than in the 0.018-in slot system. Thus, previous studies may suggest that the 0.022-in slot system is not recommended for loop mechanics. Yoshida et al<sup>23</sup> reported that the amount of force is increased by 1.5, 2.0, and 2.5 times when gable bends of  $10^\circ$ ,  $20^\circ$ , and  $30^\circ$ , respectively, were incorporated into a teardrop loop. We showed that the amounts of force generated by  $0.019 \times 0.025$ -in and  $0.021 \times 0.025$ -in teardrop loops with a height of 10 mm and an activation of 1 mm were 364 and 491 g of force, respectively, when the loops were placed at a third of the interbracket distance from the canine bracket without gable bends (Fig 6). Incorporation of gable bends of  $30^\circ$  into these loops would generate 910 and 1228 g of force of extremely heavy force for  $0.019 \times 0.025$ -in and  $0.021 \times 0.025$ -in loops, respectively, on the assumption that the force magnitude is increased by 2.5 times according to the study of Yoshida et al. This indicates that the application of such excessive retraction forces generated by loop mechanics combined with gable bends may cause damage to teeth and periodontal tissues, and the placement of gable bends should therefore be avoided not

only in the 0.022-in slot system but also in the 0.018-in slot system.

It was previously reported that a keyhole loop with duplex winding helices could decrease the retraction force and simultaneously increase the M/F ratio to a greater degree than a teardrop loop with the same height.<sup>18,23</sup> This suggests that a reduction in rigidity in a small portion of the whole configuration of a loop could reduce the retraction force and raise the M/F ratio. Thus, we hypothesized that the effect on the force system of a reduction in cross-section at certain areas of the loop might be equivalent to the effect of incorporating helices into loops. We investigated which type of cross-sectional reduction would produce the optimal force system.

Our first finding was that the retraction force was most substantially reduced with a cross-sectional reduction in the apical portion of the loop. On the other hand, the rate of decrease of the moment was much lower than that of the force. Consequently, a high M/F ratio of 8.6 was produced when the apical third of the loop was reduced by 30% in both thickness and width (Fig 4). The first analysis suggested that reduction of the apical portion of the loop would produce a higher M/F ratio than reduction of the middle or basal portion of the loop.

Our second finding was that when the length of the partial reduction in cross-section from the loop apex was increased from 0 to 3 mm, the M/F ratio also increased (Fig 5). Conversely, when the length of the



partial reduction was further increased from 3 to 4 or 5 mm, the M/F ratio decreased. Thus, in the second analysis, we concluded that a reduction in cross-section for a distance of 3 mm from the apex of the loop will produce the highest M/F ratio.

Our third finding was that both the amount of force and the moment dropped more sharply when thickness rather than width of the wire cross-section was reduced for a distance of 3 mm from the loop apex for both  $0.019 \times 0.025$ -in and  $0.021 \times 0.025$ -in teardrop loops as the reduction rate of the wire cross-section increased from 0% to 50% (Fig 6). The tested wire is a rectangular beam with a cross-section composed of thickness (shorter side) and width (longer side). When a loop is activated, the wire is bent in a flatwise direction. At this time, the moment of inertia of the cross-section of the wire is proportional to the width, however, to the cube of the thickness.<sup>27</sup> Because the flexural rigidity or resistance to bending of the wire is determined by the product of Young's modulus and the moment of inertia, the reduction in thickness of the wire has a greater impact than the width on the decrease in force. Thus, force magnitude can be more effectively decreased by reducing the thickness of the wire cross-section rather than the width. Because the decreasing rate of force was much higher than that of the moment, the M/F ratio increased from 5.8 to 9.3 (1.6 times) when thickness was reduced, and from 5.8 to 7.1 (1.2 times) when width was reduced for both  $0.019 \times 0.025$ -in and  $0.021 \times 0.025$ -in loops.

We found from the third analysis that the M/F ratio can be increased to 9.3 by reducing the thickness of the wire cross-section by 50% for a distance of 3 mm from the apex of the loop. Interestingly, there was no significant difference in the M/F ratio between the  $0.019 \times 0.025$ -in and  $0.021 \times 0.025$ -in teardrop loops. This suggests that the M/F ratio depends mainly on the vertical height or the horizontal length of the loop and the mechanical properties of the wire material, independent of the wire size.

Our fourth finding was that variation in the placement of the loop in an anteroposterior direction (loop position) had a significant impact on the amount of force, moment, and M/F ratio (Fig 7). Although it was expected that the closer the loop was placed to the bracket on 1 side, the M/F ratio was higher on that side, and the M/F ratio decreased when the loop was too close to the canine bracket.<sup>19,23</sup> This may be because the force increases more sharply than the moment as the loop moves closer to the canine bracket beyond a quarter of the interbracket distance.

The fourth analysis suggested that the highest M/F ratio of 9.3 on the anterior segment can be generated

by activation of a 10-mm-high teardrop loop, whose cross-section was reduced in thickness by 50% for a distance of 3 mm from the loop apex, and that was positioned between a quarter and a third of the interbracket distance from the canine bracket for both  $0.019 \times 0.025$ -in and  $0.021 \times 0.025$ -in wires. At this time, the maximum force magnitude was 224 g for  $0.021 \times 0.025$ -in loops. Because the maximum force magnitude was 535 g with no reduction in thickness, it could be substantially decreased simply by reducing the wire thickness of the loop. Previous studies have suggested that the ideal force magnitude for retraction of the anterior segment is approximately 250 g, and the total force should be light and should not exceed 300 g of force.<sup>21,18</sup> It was therefore considered that the simple design of a teardrop loop with partial reduction in thickness of the apical portion could generate the optimal force system and achieve better control of the anterior teeth during space closure.

Proffit<sup>18</sup> advocated the use of closing loops bent from a small wire of  $0.016 \times 0.022$  in with the 0.018-in slot system because loops with a smaller cross-section could produce a gentler force, whereas those with a larger cross-section would generate excessively heavy forces. For this reason, most clinicians practicing loop mechanics use the 0.018-in slot system rather than the 0.022-in system nowadays. However, our study suggests that the use of a  $0.019 \times 0.025$ -in or  $0.021 \times 0.025$ -in archwire in the 0.022-in slot system is exceedingly advantageous for providing the optimal force and M/F ratio and hence better control of anterior tooth movement. In addition, the bowing effect can be minimized because of the greater rigidity of the wire when compared with a  $0.017 \times 0.025$ -in archwire in the 0.018-in slot system. Also, the M/F ratio of 9.3 produced is considered to be high enough to achieve controlled tipping or bodily movement of the anterior teeth.

An advantage of using a  $0.021 \times 0.025$ -in archwire is the smaller play between the bracket slots and the archwire. This contributes to reducing the loss of anterior torque control, and the amount of uncontrolled tipping of the incisors will thus be decreased.<sup>28</sup> However, it might be difficult to engage a  $0.021 \times 0.025$ -in archwire, especially in self-ligating brackets, and excessive force and torque could be exerted on an entire dentition.

On the other hand, for  $0.019 \times 0.025$ -in teardrop loops, the force magnitude ranged from 151 to 175 g, which is much lower than the optimal force level for retraction of the anterior segment. When  $0.019 \times 0.025$ -in loops are used, it is recommended that the amount of activation of the loop should be

increased to 1.5 mm. This increases the force magnitude by nearly 1.5 times to become the optimal force for anterior tooth retraction. Loops with this wire size could also achieve controlled movement because an M/F ratio of 9.3 is produced, similar to  $0.021 \times 0.025$ -in loops. Nevertheless,  $0.019 \times 0.025$ -in loops may be slightly less capable of controlling the movement of the anterior segment because of the lower rigidity of the wire and the greater play between the brackets and the archwire when compared with  $0.021 \times 0.025$ -in loops. Clinical trials are necessary to investigate whether a  $0.019 \times 0.025$ -in or a  $0.021 \times 0.025$ -in archwire is more appropriate to achieve controlled movement of the anterior teeth.

According to our findings, the loop we designed produced an M/F ratio of 9.3, which is high enough to achieve controlled anterior tooth movement, and the optimal force level of approximately 250 g for the retraction of the anterior teeth. This force system can be generated by activating a 10-mm-high teardrop loop of a  $0.019 \times 0.025$ -in wire (on an activation of 1.5 mm) or a  $0.021 \times 0.025$ -in wire (on an activation of 1 mm) with a 50% reduction in thickness of the wire cross-section for a distance of 3 mm from the loop apex. It should be positioned between a quarter and a third of the interbracket distance from the canine bracket.

There have previously been many attempts to develop a loop design that can produce an optimal force system or to incorporate gable bends into loops to increase the M/F ratio. However, a complicated loop design is so bulky that patients could suffer from discomfort, irritation, and pain, and have difficulty in maintaining good oral hygiene. Also, the placement of gable bends could generate excessively heavy forces. In contrast, the loop we designed may be more comfortable for patients because of its simple configuration, and may deliver the optimal force and M/F ratio for retraction of the anterior teeth without adding gable bends. A further advantage is that it is easily fabricated at chairside by grinding with a turbine handpiece, and can be applied in the 0.022-in slot system.

When the loop is located at an off-center position, the M/F ratio can be raised. However, differential moments on the anterior and posterior segments are generated. A side effect of this is that vertical force will be produced on the anterior and posterior segments. We focused on the force system acting on the anterior segment to investigate the optimal loop design for achieving controlled movement of anterior teeth. Further studies are necessary to analyze the force system acting on the posterior teeth as well as the associated vertical forces developed on the anterior and posterior segments.

## CONCLUSIONS

The optimal force level and M/F ratio for achieving controlled movement of the anterior teeth can be produced by simply reducing by half the thickness of a teardrop loop (height 10 mm and cross-section  $0.019 \times 0.025$  or  $0.021 \times 0.025$  in) for a distance of 3 mm from the loop apex, and positioning it between a quarter and a third of the interbracket distance from the canine bracket.

This new closing loop produces a gentle force, even with a  $0.019 \times 0.025$ -in or  $0.021 \times 0.025$ -in wire, and a high M/F ratio of 9.3, which enables clinicians to achieve controlled tipping or bodily movement of the anterior teeth without adding gable bends. This study suggests that our loop design for the 0.022-in slot system is advantageous for providing better control of anterior tooth movement because of the higher rigidity of the wire, which minimizes the bowing effect, and the smaller play between bracket slots and the archwire; this reduces the loss of anterior torque control when compared with a  $0.017 \times 0.025$ -in archwire in the 0.018-in slot system.

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