Mechanical Force System of Double Key Loop With Finite Element Analysis

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Research article

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Abstract

Background: The mechanics of double key loop (DKL) was not well defined and this finite element study was designed to explore its force system.

Methods: Simplified 3-dimensional finite element model of single and double key loops with archwire between lateral incisor and second premolar was established in Ansys Workbench. Activation in Type-1 (retraction at distal end), Type-2 (retraction at distal key) and Type-3 (Type-2 plus ligation between keys) were simulated. The vertical force, load/deflection ratio and moment/force ratio of stainless steel and TMA loops were calculated and compared.

Results: Double key loop generated about 40% force of single key loop. Type-2 loading of DKL showed higher L/D ratio than in Type-1 loading with similar M/F ratio. Type-3 loading of DKL showed the highest M/F ratio with similar L/D ratio as single key loop. The M/F ratio in Type-3 loading increased with the decrease of retraction force. DKL of TMA produced about 40% of force and moment compared to those of SS in all loading types. When activated at equal distance bellow 1mm, the M/F ratio of SS and TMA DKL with equal preactivation angle were almost the same.

Conclusion: M/F ratio on anterior teeth increases with preactivation angle and deactivation of DKL. M/F ratio at certain distance of activation depends mainly on preactivation angle instead of wire material. TMA is recommended as substitute of SS in DKL for lower magnitude of force.

1. Background

In orthodontic treatment with premolar extraction, sliding and closing loop are two major techniques to close the space. Although sliding mechanics is widely used in clinic with advantages of simplified mechanics, increased patient comfort and reduced chair time[1,2], loop mechanics is still thought to be more efficient in controlling teeth movement pattern[3]. Orthodontic loops are frictionless and all the generated force will be fully expressed against the brackets and finally to teeth after deactivation[4]. Some clinicians still prefer loop mechanics to sliding mechanics[5,6].

Closing loop with different configurations, such as T loop, teardrop loop, L loop, mushroom loop, were used in clinic and they need individual adjustments according to the clinical experience of orthodontists[4,7]. Load deflection ratio (L/D), vertical force and moment to force ratio (M/F) are three important indexes for evaluation of different loops and M/F ratio is the most critical one in loop mechanics. Generally, force system with M/F ratio of 7 mm induced controlled tipping and M/F ratio above 10 was required for translation of teeth[8,9]. As reported in previous experimental and analytical researches, M/F ratio varied with wire material, cross section, height, width and configuration of loops[10–14]. Preactivation methods such as gable bend and vertical step diversified the M/F ratio[15–18]. The M/F ratio was also reported to change with the distance of activation[19,20].

Double key loop (DKL) is a special method advocated by John Parker to close space with straight wire appliance[21]. Normally, DKL is composed of two key hole like vertical loops at the mesial and distal interproximal position of canine. Loading at distal end, distal key and additional ligation between keys are the three major loading types of DKL, which provide advantages of flexible force system and effective control of anterior torque[22]. Retrospective clinical studies of Dr. Kim and Chen reported the high efficiency of DKL in the vertical and torque control of upper anterior teeth[23,24]. Clinicians were interested in its mechanical property, and several relevant studies tried to explore precise control method of DKL. Dobranszki used photoelastic models to compare the force response of teeth subjected to DKL and confirmed that vertical force on anterior teeth varied with the loading types[25]. Tábitha used finite element method to investigate the force and deformation of DKL but no detailed M/F ratio results were provided[26].

To provide a preliminary guide for application of DKL, finite element method was used in this study to explore the effect of wire material, loading types and preactivation angle on the mechanical force system of DKL.

2. Materials And Methods

Archwire between upper lateral incisor and second premolar with single key loop and double key loop was established in finite element analysis software Ansys Workbench 17.0 (ANSYS, USA). The cross-section of archwire was 0.019 × 0.025 inch rectangular and the configuration of key loop was shown in Fig. 1. Hight and width of key loop was 6 mm and 4 mm respectively. Key loops were at the mesial and distal interproximal position of canine. The archwire was divided into several parts and bonded contacts were added between them to calculate the force and moments at specific position. Automatic meshing was finished in Workbench and 174830 nodes and 108039 elements were attained (Fig. 2-A). Wire material was defined as stainless steel (SS) with elastic property of Yang's modulus 168 GPa, Possion's ratio 0.3, and titanium-molybdenum alloy (TMA) with Yang's modulus 66 GPa, Possion's ratio 0.3[5,27].

To simulate the activation of key loops, the mesial end was fixed in six degrees of freedom (three displacement along and three rotations around the three orthogonal axes). Vertical (Z axis) displacement of distal end was set as 0 mm to simulate the sliding of archwire through the bracket slot of second premolar. Force was applied on different position to simulate three types of loading (Fig. 3). For Type-1 loading, horizontal force was applied to the distal end. For Type-2 loading, force was applied between the distal key and the tube of second molar. For Type-3 loading, a spring was added between mesial and distal loops to simulate preactivation, then retraction force was applied as in Type 2. Stiffness of the spring was set as 15 N/mm. Preliminary experiments verified that preloading of 7.1 N, 14.2 N and 21.3 N on spring generated upward bending of distal wire in SS DKL to preactivation angles (θ) of 5°, 10° and 15° respectively (Fig. 2-B). When the distal end was constrained in vertical component, simulating the engagement of preactivated DKL in premolar brackets, the residual tension in spring was 1.86 N, 3.71 N and 5.57 N respectively. For TMA wire, preloading of 6 N, 12.4 N, 18.9 N and 25.3 N was applied accordingly to generate preactivation angles of DKL of5°, 10°, 15° and 20°, and the residual tension after engagement was 0.97 N, 2.07 N, 3.18 N and 4.28 N respectively. The mesial displacement of distal end for each preactivation angle was calculated and this was set as the neutral position.

Retraction force from 1 to 8 N was applied in each loading condition at interval of 1 N and all the data of reaction force and resultant displacement were collected. Force and moment reaction on the mesial end were recorded. Horizontal displacement of distal end was recorded as extension of the archwire. Load deflection ratio (L/D) and moment/force ratio (M/F) were calculated accordingly.

3. Results

Deformation of SS key loops after loading of 5 N was showed in Fig. 4 and showed different patterns. The horizontal part of single loop showed the least distal extension. In DKL, both mesial and distal loops were activated. In Type-1 loading, the distal loop opened greater than the mesial loop did, and the distal loop moved occlusally. In Type-2 loading, mesial loop opened greater than the distal loop did, and the horizontal archwire was almost at the original level. Type-3 loading activated the mesial and distal loop to almost the same distance and the distal loop shift occlusally a little.

The displacement of distal end under retraction force on SS loops was listed in Table 1 and Fig. 5-A. For the single key loop in Type-1 loading, L/D ratio in horizontal direction was around 10.2 N/mm. For the DKL in Type-1 loading, the horizontal L/D ratio was 4.37 N/mm, about 43% of single key loop. For DKL in Type-2 loading, its horizontal L/D ratio of 6.05 N/mm was higher than that in Type-1 loading, but lower than that in Type-3 loading. The distal extension of DKL with preactivation angles of 5°, 10° and 15° in Type-3 loading started at retraction force of about 1 N, 2 N and 4 N respectively. L/D ratio of DKL at preactivation angle of 5° was 9.37 N/mm, and it increased to 10.8 N/mm when preactivation angle was up to 15°. L/D ratio of DKL in Type-3 loading was close to that of single key loop in Type-1 loading.

Table 1
Displacement (mm) of distal end in stainless steel single and double key loops under different loading types

Force (N)	Type-1 Single	Type-1	Type-2	Type-3 +5	Type-3 +10	Type-3 +15
1	0.098	0.229	0.165	0.003	0.004	0.004
2	0.196	0.458	0.331	0.090	0.009	0.009
3	0.294	0.687	0.496	0.198	0.054	0.015
4	0.392	0.915	0.661	0.305	0.143	0.024
5	0.491	1.144	0.826	0.414	0.241	0.107
6	0.589	1.373	0.992	0.523	0.350	0.196
7	0.687	1.602	1.157	0.632	0.461	0.287
8	0.785	1.831	1.322	0.740	0.567	0.394

Table 2
Displacement (mm) of distal end in TMA single and double key loops under different loading types

Force (N)	Type-1 Single	Type-1	Type-2	Type-3 +5	Type-3 +10	Type-3 +15
1	0.250	0.582	0.421	0.120	0.012	0.024
2	0.499	1.165	0.832	0.371	0.191	0.063
3	0.749	1.747	1.262	0.622	0.437	0.272
4	0.999	2.330	1.683	0.873	0.688	0.512
5	1.249	2.912	2.103	1.124	0.939	0.763
6	1.498	3.495	2.524	1.374	1.190	1.013
7	1.748	4.077	2.945	1.625	1.440	1.264
8	1.998	4.660	3.365	1.876	1.691	1.515

For TMA loops in Type-1 loading, the L/D ratio of single key loop was 4.00 N/mm and L/D ratio of DKL was 1.72 N/mm. L/D ratio of DKL in Type-2 loading was 2.37 N/mm. The distal extension of TMA DKL with preactivation angles of 5°, 10° and 15° in Type-3 loading started at retraction force of about 0.5 N, 1 N and 2 N respectively. L/D ratio of TMA DKL in Type-3 loading was close to that of single TMA key loop in Type-1 loading, keeping at around 4 N/mm. The results were approximately 40% of the corresponding value of SS key loops (Table 2, Fig. 5-B).

Table 3
Reaction force and moment on mesial end of stainless steel key loops and the moment/force ratio in different loading types

	Retraction Force (N)	X (N)	Z (N)	Moment (N.mm)	M/F (mm)
Type-1 Single	2	2.00	-0.742	7.06	3.53
	4	4.00	-1.483	14.12	3.53
	6	6.00	-2.225	21.18	3.53
Type-1	2	2.00	-0.417	7.11	3.56
	4	4.00	-0.835	14.22	3.56
	6	6.00	-1.252	21.33	3.56
Type-2	2	1.98	0.223	6.48	3.27
	4	3.96	0.445	12.97	3.27
	6	5.94	0.668	19.46	3.27
Type-3 + 5	0	0.00	-0.517	8.79	/
	1	0.99	-0.308	9.54	9.62
	2	1.98	-0.167	11.43	5.77
	4	3.96	-0.058	18.20	4.59
	6	5.94	0.028	25.35	4.26
Type-3 + 10	0	0.00	-1.105	18.78	/
	1	0.99	-0.895	19.51	19.69
	2	1.98	-0.685	20.24	10.21
	4	3.96	-0.379	23.64	5.96
	6	5.94	-0.202	29.26	4.92
Type-3 + 15	0	0.00	-1.690	28.73	/
	1	0.99	-1.480	29.46	29.73
	2	1.98	-1.273	30.23	15.26
	4	3.96	-0.862	31.83	8.03
	6	5.94	-0.591	35.84	6.03

Table 4
Reaction force and moment on mesial end of TMA key loops and the moment/force ratio in different loading types

	Retraction Force (N)	X (N)	Z (N)	Moment (N.mm)	M/F (mm)
Type-1 Single	2	2.00	-0.742	7.06	3.53
	4	4.00	-1.483	14.12	3.53
	6	6.00	-2.225	21.18	3.53
Type-1	2	2.00	-0.417	7.11	3.56
	4	4.00	-0.835	14.22	3.56
	6	6.00	-1.252	21.33	3.56
Type-2	2	1.98	0.223	6.48	3.27
	4	3.96	0.445	12.97	3.27
	6	5.94	0.668	19.46	3.27
Type-3 + 5	0	0.00	-0.023	3.68	/
	1	0.99	-0.064	5.39	5.44
	2	1.98	-0.003	9.14	4.61
	4	3.96	0.027	16.74	4.22
	6	5.94	0.086	24.34	4.10
Type-3 + 10	0	0.00	-0.479	8.15	/
	1	0.99	-0.291	9.24	9.32
	2	1.98	-0.164	11.38	5.74
	4	3.96	-0.069	18.39	4.64
	6	5.94	-0.010	25.99	4.37
Type-3 + 15	0	0.00	-0.745	12.67	/
	1	0.99	-0.557	13.76	13.88
	2	1.98	-0.378	15.02	7.58
	4	3.96	-0.167	20.05	5.06
	6	5.94	-0.108	27.66	4.65

As to the vertical fore at the mesial end of SS single and double key loop, it was negative in Type-1 loading regardless of the force level, indicating an extrusive force acted on the anterior teeth. On the contrary, vertical force at the mesial end was positive for DKL in Type-2 loading, meaning an intrusive force on anterior teeth. Vertical force of DKL at mesial end in Type-3 loading after engagement (Retraction force = 0) was extrusive and the magnitude increased with the preactivation angle. At preactivation angle of 5°, the extrusive force decreased with the increase of retraction force and the vertical force became intrusive when retraction force was above 6 N. However, the vertical force kept extrusive in Type-3 loading at preactivation angles of 10° and 15° (Table 3). For TMA loops, vertical forces at mesial end were similar in direction as those of SS loops, but the magnitudes were less when subjected to the same retraction force. In Type-3 loading of TMA DKL with preactivation angle of 5°, the vertical force become intrusive when the retraction force was up to 4 N (Table 4).

Moment on the mesial end in all loading types increased with the increased distal traction force (Table 3). For SS loops in Type-1 loading, the moment increased proportionally and the M/F ratio kept at 3.53 mm. Adding of a parallel key loop in DKL induced no change of the M/F ratio. Moment in Type-2 loading of DKL also increased proportionally with the distal force and the M/F ratio increased to 3.27 mm, which was close to that in Type-1 loading.

Moment in Type-3 loading of DKL increased with the preactivation angle and retraction force. After simulative engagement of SS DKL in bracket without retraction, the moment on mesial end was 8.79, 18.78 and 28.73 N·mm at preactivation angles of 5°, 10° and 15°. All M/F ratios in Type-3 loading of DKL were higher than in Type1 and Type-2 loading. As the retraction force raised up, the moment at mesial end increased but the M/F ratio decreased inversely. The highest M/F ratio in the conditions with preactivation angles of 5°, 10° and 15° were 9.62, 19.69 and 29.73 mm respectively under 1 N retraction force. The M/F ratios under 6 N retraction force were 4.26, 4.92 and 6.03 mm respectively, showing less difference (Table 3).

For TMA loops (Table 4), the moments at mesial in Type-1 and Type-2 loadings under equal retraction force were almost the same and the corresponding M/F ratios were the same as that of SS loops. In Type-3 loading of DKL, the moment at mesial end after simulative engagement was 3.68, 8.15 and 12.67 N.mm at preactivation angles of 5°, 10° and 15°. M/F ratio of TMA DKL under the same retraction force was lower than that of SS DKL with equal preactivation angle. The highest M/F ratio at preactivation angles of 5°, 10° and 15° was 5.44, 9.32 and 13.88 mm under 1 N retraction force. Its M/F ratio under 6 N retraction force varied between 4.10 and 4.65 mm.

Change of M/F ratio against the distal retraction force was showed in Fig. 6. At the same level of retraction force, the M/F ratio increased with the practivation angle. The M/F ratio of SS DKL was higher than that of TMA DKL under the same level of retraction force. Almost overlapping in the fitting curve of SS + 5 and TMA + 10, and overlapping of SS + 10 and TMA + 20 suggested their equal M/F ratio under the same retraction force.

As showed in Fig. 7, the M/F ratio decreased with the extension of distal end. M/F ratio in all conditions was all above 4.03 mm. M/F of DKL with higher preactivation angle was above those with lower angles. At an equal amount of distal extension, M/F ratio of DKL increased with the practivation angle. The fitting curves of SS and TMA DKL with equal preactivation angle were close to each other, indicating similar M/F ration at the same distance of activation.

4. Discussion

DKL was advocated for extraction space closure but its mechanical property was not well defined in previous literature. In the commercial DKL products, the most common ordered size of SS loops was 0.019 × 0.025 inch. Finite element analysis was widely used in researches of orthodontic biomechanics, including appliances, wire materials, loops and force direction control[11,13,16,17,28]. As for orthodontic loops, the analytical results were comparable and consistent with experimental data in previous research[20,29], proving the credibility of finite element analysis in similar researches. The actual force exerted on tooth was very complicated and influenced by many factors, such as elastic property of periodontic tissue, root length, height of alveolar bone, clearance between archwire and bracket slot. In this study, the finite element model was simplified to be flat without teeth and curvature for comparison of different loading conditions and force level.

4.1. Single key Vs double key loop.

It was obvious that double key loop had a lower L/D ratio than singe key loop did. For a single key loop, force over 10 N was needed to activate it for 1 mm in Type-1 loading. This is quite high and it was seldom used in clinic. SS DKL got activation of 1 mm under 4.37 N force in Type-1 loading, which was acceptable in loop mechanics for clinicians. Former studies proved that cross-section, height of loop and wire material were three major factors affecting the L/D ratio of closing loops[11,13]. When switched to TMA, the force required for 1 mm activation dropped about 60% for single and double key loops. DKL and TMA were superior to single key loop and SS in terms of wire rigidity.

4.2. L/D ratio of DKL

L/D ratio of DKL was also affected by the loading types. In Type-2 loading, the L/D ratio of SS and TMA loops was about 1.35 times higher than that in Type-1 loading. The reason could be the change in location of force application. When loaded at distal key, deformation of mesial key was almost the same, but the distal loop showed distal tipping instead of loop opening (Fig. 4). When loaded in Type-3, the L/D ratio increased dramatically to around 10 and 4 N/mm for SS and TMA DKLs, which were close to that of single key loops. Ligation between double keys was made with 0.0025 inch SS wire in clinic and this kept the keys from separating apart. An elastic spring with high stiffness up to 15 N/mm was used to simulate the ligation in the model. Retraction force on distal key was transmitted through the spring to mesial key and finally to the mesial end. Hence, DKL behaved similarly to single key loop in L/D ratio.

For DKL with preactivation in Type-3 loading, distal extension was restricted when the retraction force was too low and the retraction force just induced distal tipping and occlusal movement of distal key loop. The initial force level to start distal extension varied with the wire material and preactivation angle. Initial activating force increased with the preactivation angle, and SS DKL needed higher force to start activation than TMA DKL. After initial activation, the DKL with preactivation showed linear extension as in other loading conditions with similar L/D ratio of single key loop.

4.3. Vertical force

Vertical force is important for appraisement of loops. Key loops in Type-1 loading exerted extrusive force at the mesial end as reported in former research on T loops[11,16]. In Type-2 loading of DKL, retraction force induced distal tipping of distal loop and brought the mesial archwire and key loop above the original level, inducing intrusive force on the mesial end. These results were consistent with the photoelastic results of Dobranszki[25]. As for Type-3 loading of DKL, a condition normally used for correction of deep bite in clinic, there was extrusive force at mesial end. The main reason was that molar tube occlusal to key loops induced a retraction force with extrusive component at distal key loop. Another reason might be the exclusion of canine in the model. As demonstrated in Fig. 4-D, ligation between key loops brought the horizontal wire between loops occlusally. After engagement in clinic, the canine would be extruded while mesial and distal teeth would be intruded due to the elasticity of periodontic tissue. Establishment of integrated model with bone, periodontal tissue, teeth and orthodontic appliance was necessary to fully interpret the vertical reaction of teeth to DKL.

4.4. M/F of key loops

M/F ratio is the key factor controlling moving pattern of tooth[8]. The M/F ratio is determined by the cross-section, height, loop design and preactivation[11–13]. In this study, the M/F of key loops in Type-1 loading and Type-2 loading was constant in the process of activation and did not change with the wire material. Single and double key loops showed similar M/F ratio in Type-1 loading. In Type-2 loading, the M/F ratio of DKL was close to that in Type-1 loading. However, M/F ratio should be above 7 mm to attain controlled tipping of teeth, and higher than 10 mm to achieve bodily movement[8]. So single and double key loops in plain wire were not enough to achieve well control of space closure.

Methods to increase M/F ratio of closing loops include reverse curve of Spee, V bend and gable bend[15,17,19]. The special preactivation method for DKL was ligation between the mesial and distal key loops, which generated upward bending of mesial and distal archwire. Although the horizontal archwire beyond the key loops was still flat, there has been a curvature in the whole archwire, which was similar as reverse curve of Spee and gable bend. Engagement of preactivated DKL into bracket slots induced positive initial moment on anterior teeth. As showed in Table 3 and Table 4, this initial moment increased with the practivation angle and rigidity of wire material. Retraction force at distal key pulled the distal key loop backwards and induced additional positive moment on mesial end. However, the M/F ratio decreased with the increase of retraction force. Taking SS DKL with preactivation angle of 10° for example, the M/F ratio was 19.69 mm when the retraction force was 1 N, but it dropped to 4.92 mm when the retraction force was 6 N. In another view of point, the M/F ratio increased with the deactivation of DKL from 6 N to 1 N in Type-3 loading. The resultant movement of anterior teeth will start from control tipping then turn into translation and root torqueing. When the retraction force comes to null, there will be only positive moment at the mesial end, indicating further anterior root torqueing movement.

For traditional closing loops, preactivation status, including the depth of reverse curve and angle of gable bends, tends to be weakened after several weeks in the mouth. Preactivation through ligation in DKL shows minor change because additional force is stored in deformation of vertical legs and they are free from masticatory force. It is very important for clinicians to prolong the appointment intervals up to six weeks and give enough time for the expression of positive torque on anterior teeth[22]. As supposed by Dr. Kumar, the key indication for further activation was whether the angle of canine had become normal and the arch had been levelled or not[21].

4.5. Optimal loading condition

The force system of DKL is quite complicated and it is not easy for clinicians to decide a suitable loading condition. As showed in Fig. 6, the M/F ratio of DKL in Type-3 loading under the same level of retraction force increased with the preactivation angle. To attain similar M/F ration, TMA DKL required twice preactivation angle of SS DKL.

In orthodontic clinic, it is more convenient to observe the distal extension of archwire than to measure the force on the ligature wire between distal key loop and molar tube. Normally, orthodontists activate closing loops up to 1 mm in each visit and wait enough time for the next activation. Figure 7 showed that, M/F ratio of DKL at a certain distance of activation in Type-3 loading depended mainly on the preactivation angle, while the wire material had no obvious impact. It is reasonable to select preactivation angle according the desired change of anterior torque based on the original status. To achieve similar torque control on anterior teeth with the same preactivation angle, TMA DKL could provide 2.5 times longer distance of activation at equal retraction force, or provide about 60% lower magnitude of force and moment at the same distance of activation, as compared to SS DKL. There could be several combinations of loop materials, preactivation angle and activation distance. These data were instructive for clinicians to make a good decision.

Traditionally, the optimal force was 3.1 N for upper anterior teeth was and 2.6 N for lower anterior teeth[30,31]. However, latest research suggested that force with lower magnitude could be optimal for bodily orthodontic movement[32]. It was worth emphasizing that activation of 0.019 × 0.025 inch SS DKL up to 1 mm in Type-3 required force that was quite heavy. Unsurprisingly, this was not realized by clinicians and it called for evidence from experimental researches. If testified in actual measurement, use of SS DKL for space closure should be reconsidered. TMA DKL in the same size required about 40% force of SS DKL for the same loading condition. Change of DKL material into TMA is a good choice, or the cross-section and configuration should be optimized for SS DKL.

5. Conclusion

The force system of DKL changed with loading types, preactivation angle and wire material. Type-2 loading of DKL showed higher L/D ratio than Type-1 loading. Type-3 loading showed the highest M/F ratio with similar L/D ratio of single key loop. M/F ratio of DKL on anterior teeth in Type-3 loading increases with the preactivation angle. M/F ratio of DKL in Type-3 loading increased in the process of deactivation and M/F ratio at certain distance of activation depended mainly on preactivation angle instead of wire material. DKL of TMA was recommended as substitute of SS for lower magnitude of force.

Abbreviations

DKL
double key loop
SS
Stainless steel
TMA
Titanium molybdenum alloy
L/D ratio
Load deflection ratio
M/F ratio
Moment/force ratio
N
Newton

Declarations

Availability of data and materials

All data generated or analysed during this study are included in this published article.

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Contributions

JL: Investigation/Visualization/Writing-Original Draft. **DQ Z:** Formal analysis/ Validation/Writing-Original Draft. **LY X:** Data analysis. **SX C:** Data Curation/Data analysis. **JQ G:** Methodology. **J C:** Writing-Review & Editing. **JH S:** Conceptualization/ Funding acquisition/Writing - Review & Editing.

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Ethics declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Written informed consent was obtained from all participants in this study.

Competing interests

The authors have no conflicts of interest relevant to this article.

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Figures

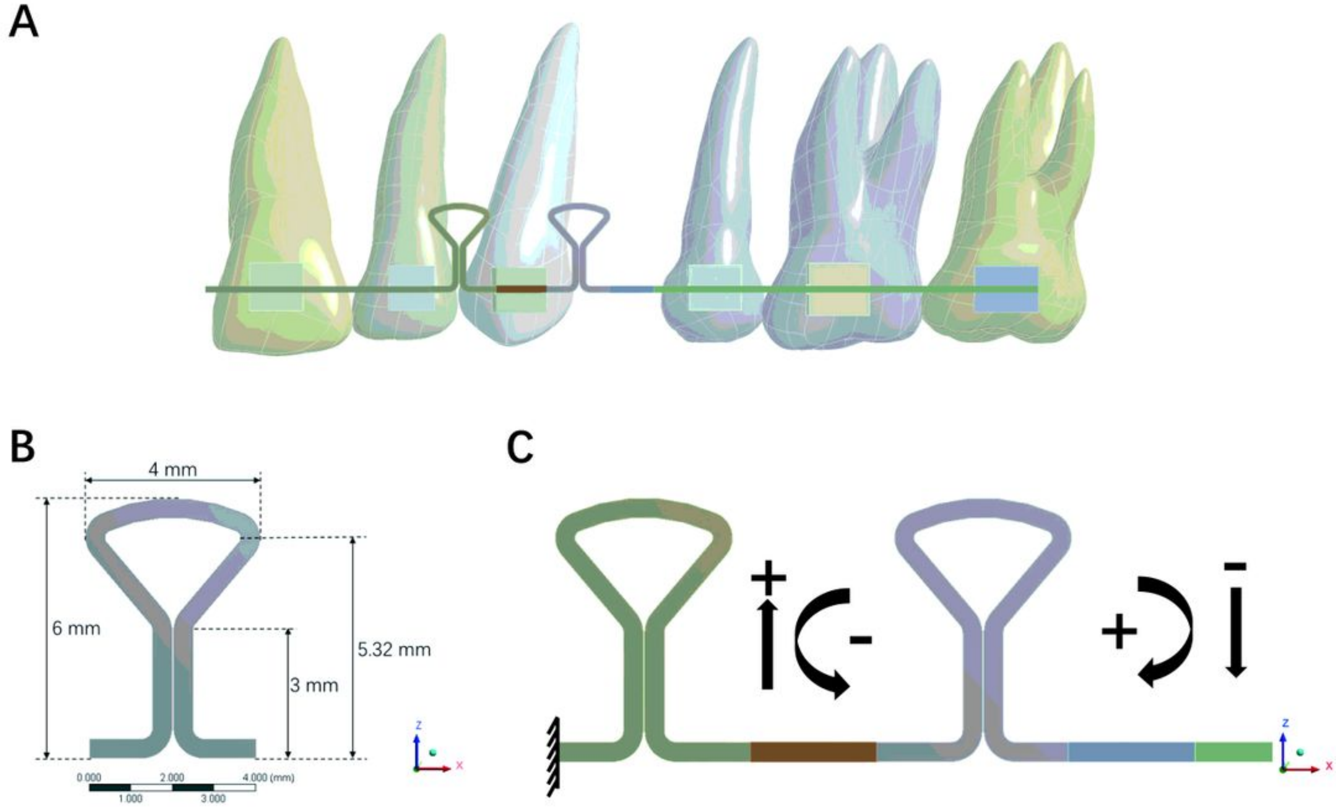

Figure 1

Configuration and dimension of double key loop (DKL): A, Clinical use of DKL for closure of upper premolar extraction space. B, Dimension of key loop, with height of 6 mm and width of 4 mm. C, Definition of forces and moments. Positive force indicated intrusion of teeth and negative force indicated extrusion of teeth. Positive moments rotated the anterior tooth clockwise, and negative moments rotated the anterior tooth counterclockwise.

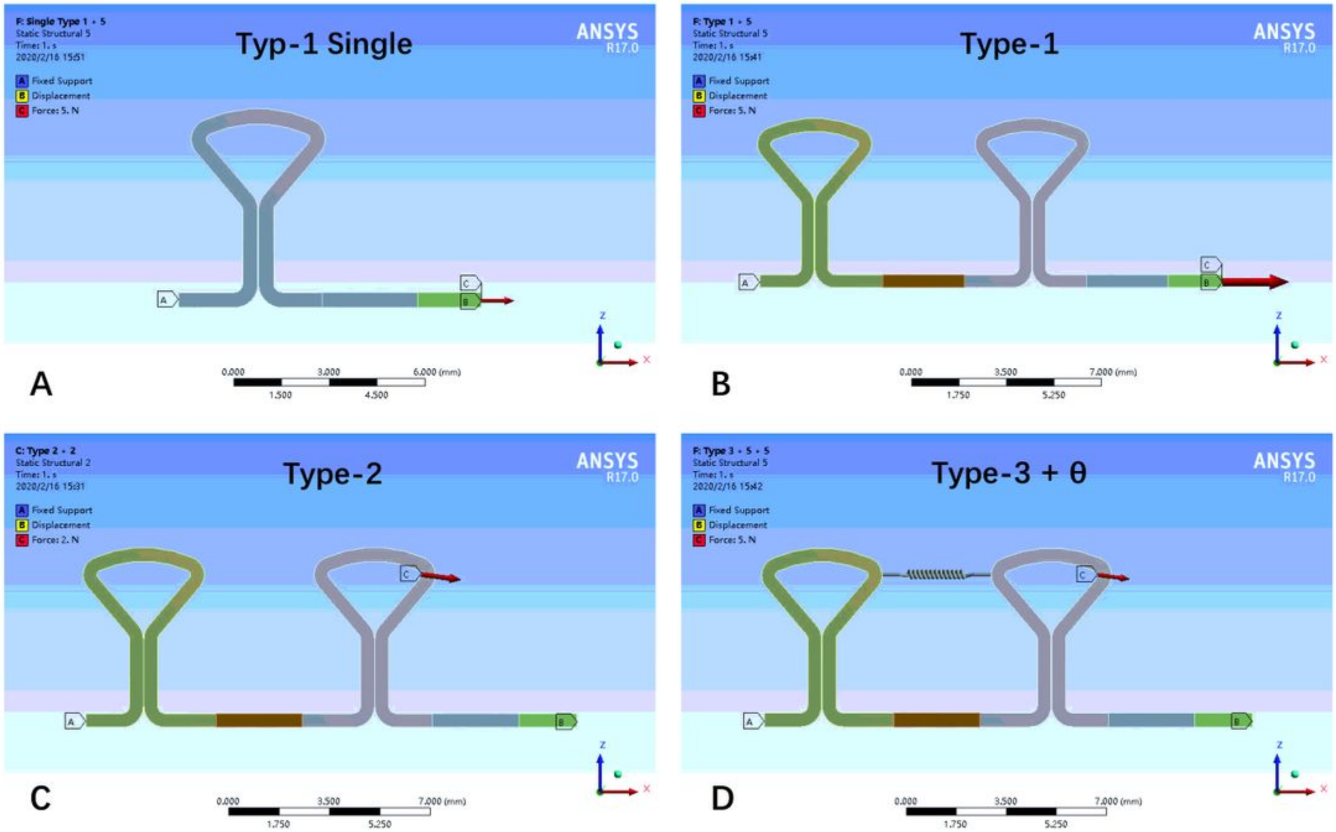

Figure 2

Meshing and preactivation of DKL. A, Meshing of DKL model with refined elements. B, Archwire with key loops was fixed on the mesial end and the distal end was free. Simulative preactivation of DKL with a spring generated curvature between mesial and distal archwire. Angle between distal archwire and horizontal line was named preactivation angle (θ).

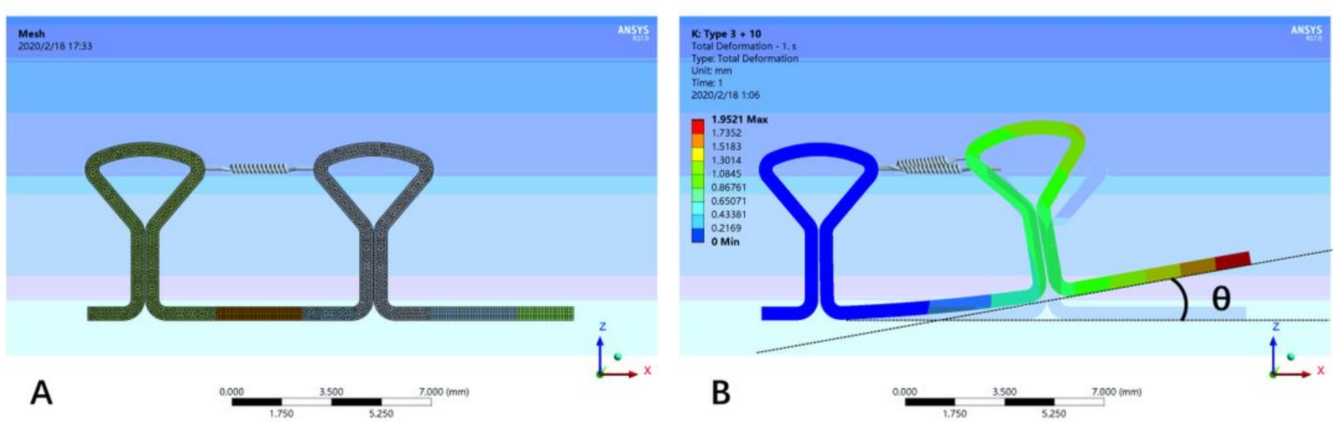

Figure 3

Loading conditions of key loops. Archwire with key loops was fixed on the mesial end and the distal end was constrained in vertical component. A, Single key loop subjected to horizontal force at the distal end. B, DKL subjected to horizontal force at the distal end. C, DKL subjected to retraction force from distal key to tube of second molar. D, DKL subjected to retraction force from distal key to tube of second molar plus a spring between key loops generating preactivation angle (θ).

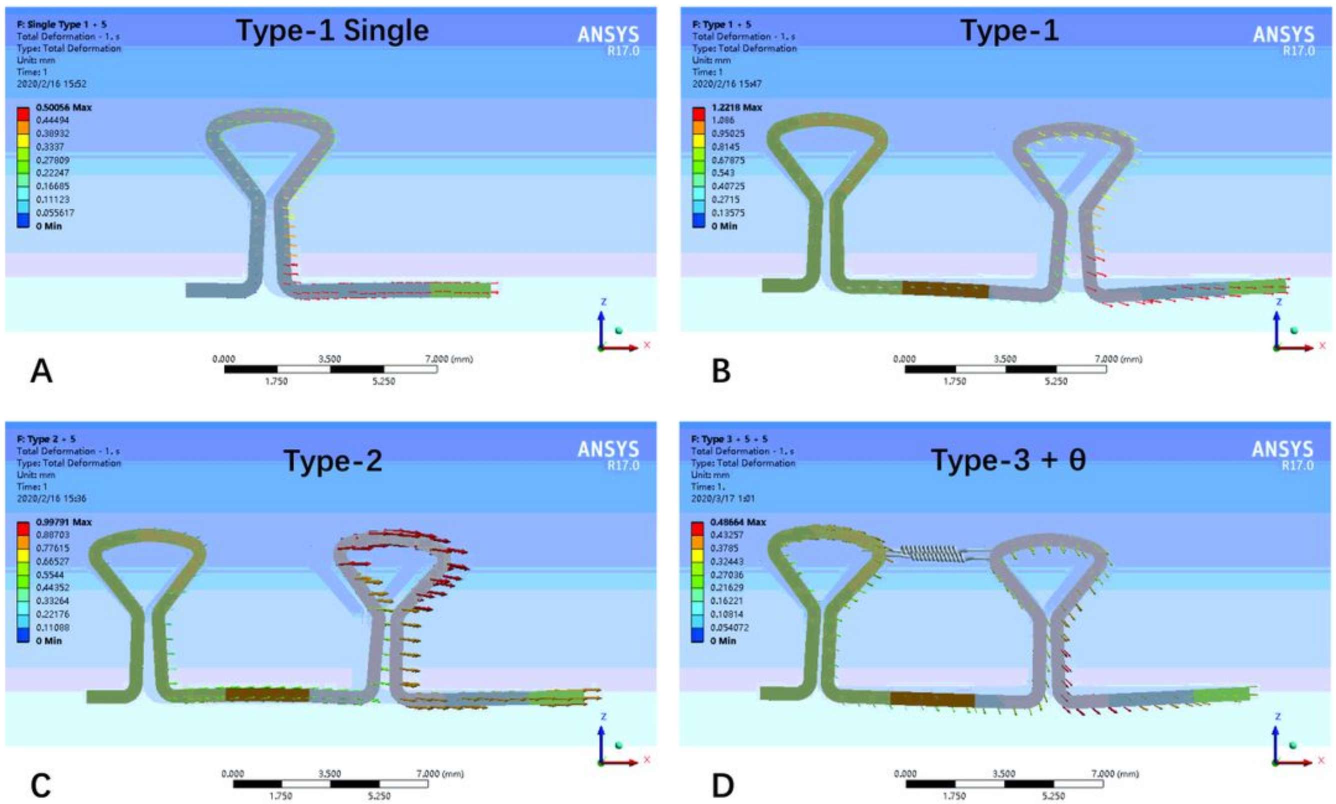

Figure 4

Typical porportional displacement vector of key loops after loading of 5 N distal retraction force in different types. Displacement was showed in true scale. The direction of vectors indicated the direction of deformation and the length of vectors indicated the magnitude of displacement.

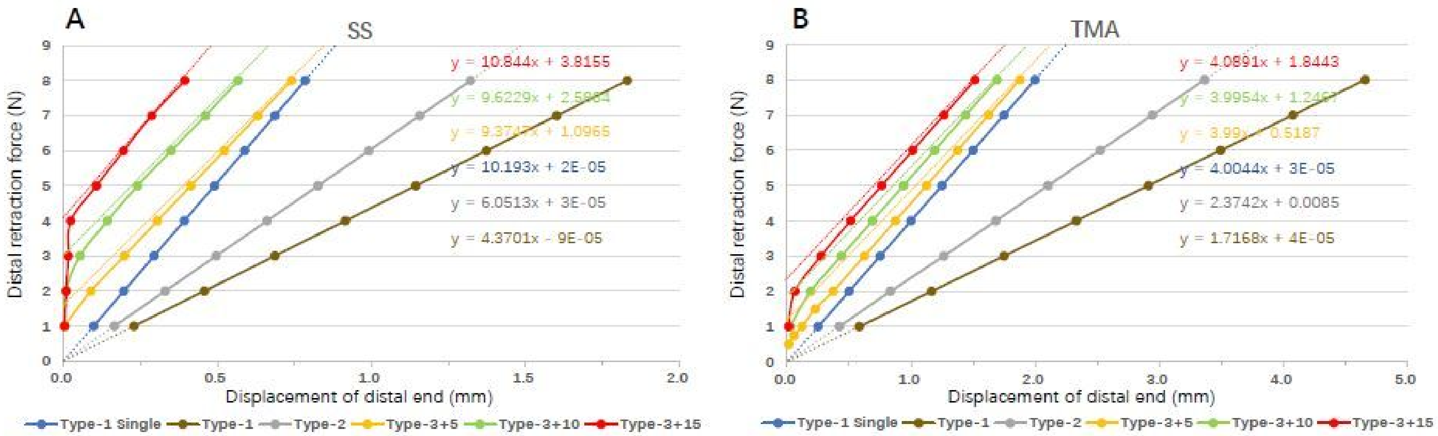

Figure 5

Linear fitting curve of distal retraction force against displacement for SS DKL (A) and TMA DKL (B) in different loading types. The fitted equations were display in corresponding colour and the gradient of fitting curve indicated the load/deflection ratio of each loading condition.

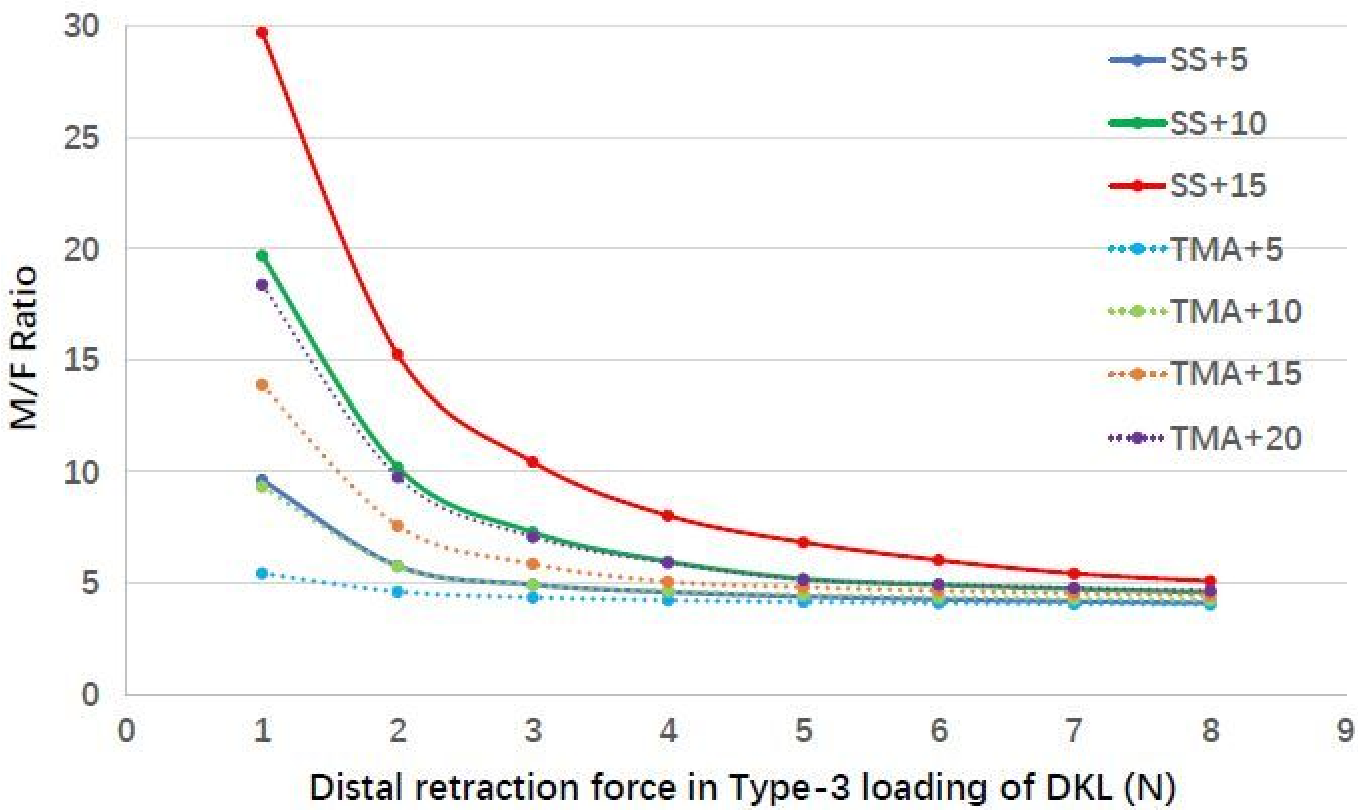

Figure 6

Fitting curve of M/F ratio against distal retraction force of SS and TMA DKL in Type-3 loading with different preactivation angles.

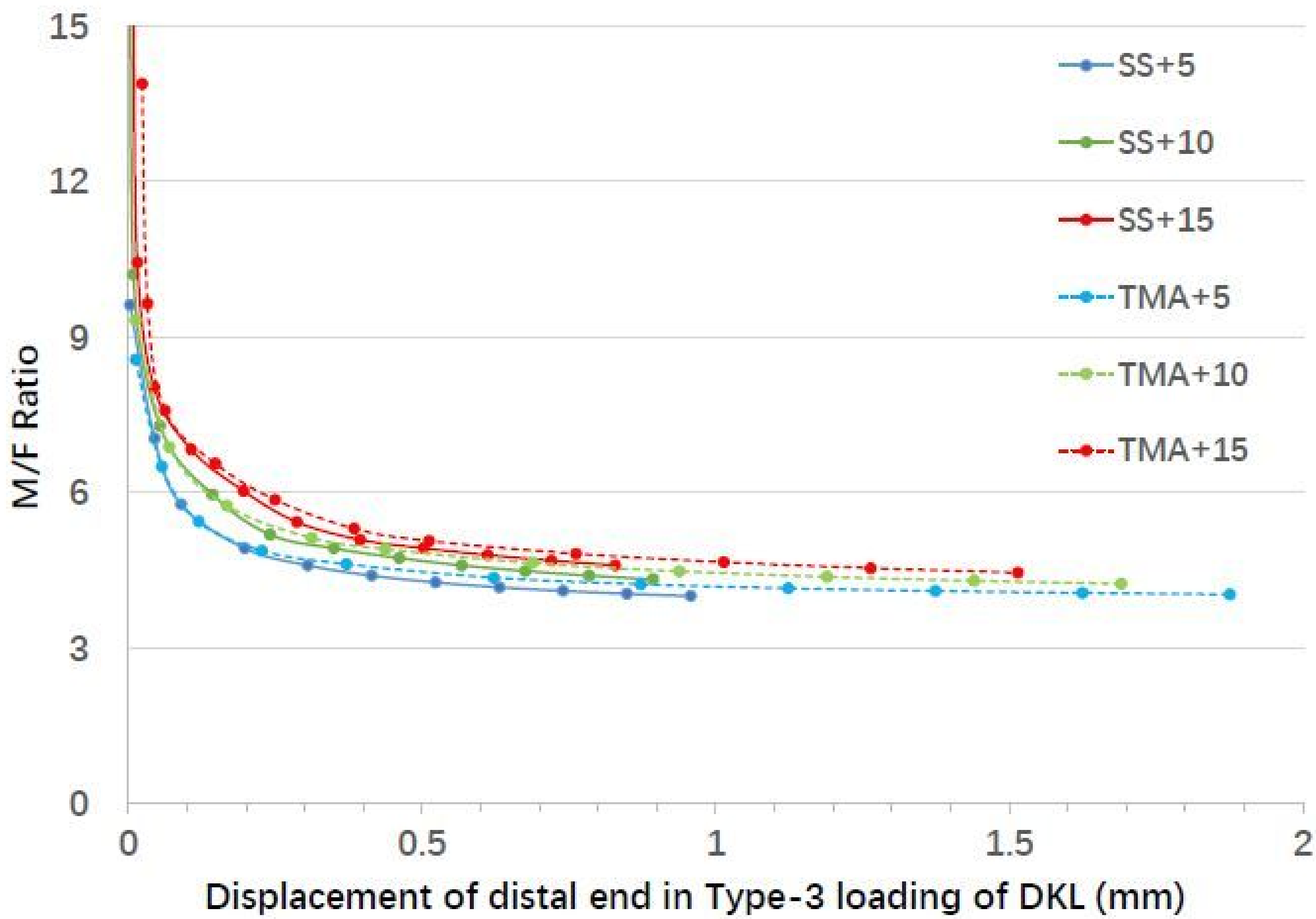

Figure 7

Fitting curve of M/F ratio against distal displacement of SS and TMA DKL in Type-3 loading with different preactivation angles.