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Evaluation and Comparision of Biomechanical Properties of Different Loops for En Masse Retraction of Anterior Teeth Using Finite Element Analysis: An In-Vitro Study.

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Abstract

Background: To evaluate and compare the biomechanical properties of various retraction loops using Finite Element Method.

Materials and method: Using Finite element method (Ansys V15 software) 25 loops were constructed with 0.016×0.022 inch stainless steel and 0.017×0.025 inch titanium molybdenum wire.

Results: The M/F ratio produced was higher and F/D rate produced was least for Opus loop compared to Snail loop, Teardrop loop, T-loop, and Teardrop with helix loop.

Conclusions: For optimum delivery of M/F ratio using snail loop must be prepared in either 0.016×0.022 SS wire with preactivation bend of 10° after D2 displacement or 0.017×0.025 TMA wire with preactivation bend of 10° and 20° after D1 displacement.

Keywords: Snail loop, Opus loop, Teardrop loop, T-loop, and Teardrop with helix loop and FEM.

Introduction

Orthodontic appliances (wires, brackets, elastics etc.) inserted and activated by the orthodontist brings about the tooth movement by application of force to the teeth. Appliances which are used in orthodontics consist of force system which produces forces and moments. These systems bring about tooth movement in predictable and controllable manner. Regulation of tooth movement by orthodontics can be done by altering the ratio of moment to force. The basis of the orthodontic tooth movement lies in clinical application of the biomechanical concepts. Orthodontic tooth movement during space closure in achieved through 2 types of mechanics. This first type, segmental or sectional mechanics, involving closing loops fabricated either in a full or sectional arch wire. The teeth move through activation of the wire loop, which can be designed to provide a low load deflection rate and a controlled moment to force ratio.

The second type of mechanics is sliding mechanics. This type of mechanics involves the moving of archwire through brackets and tubes / bracket along archwire. In standard edgewise technique rectangular archwires could not effectively slide through bracket-slots due to the need for and presence of 1^{st}, 2^{nd} and 3^{rd} order bends in the archwires and hence closing loop arches were used for space closure. When sliding mechanics is used, friction occurs at bracket wire interface.

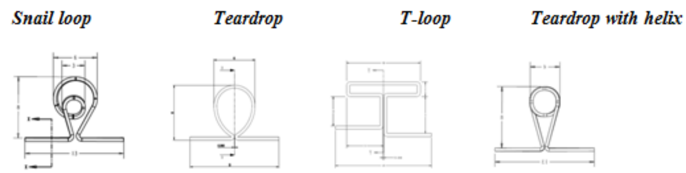
Orthodontic appliances apply forces which is dispel as friction and some of them are mediated to tooth structure to bring about the tooth movement. Therefore, maximum biological response occurs only when applied force is of sufficient magnitude to adequately overcome friction and lie within the optimum forces necessary for movement of the tooth.[1, 2]

Stainless steel and titanium molybdenum wires were used for fabrication of loops. Stainless steel wires have a range of values both for elasticity and yield strength related to the change in different parameters at their production stage such as freezing and incandescence during cold working. Stainless steel wires produce higher forces applied during shorter time periods since they have lower spring back ability and also store less energy compared to those of beta-titanium or nickel-titanium.[3] The open vertical loop, closed vertical loop, bull loop, omega loop, T loop, teardrop loop, delta loop and opus loop are various available loop design which are used in sectional mechanics for space closure.

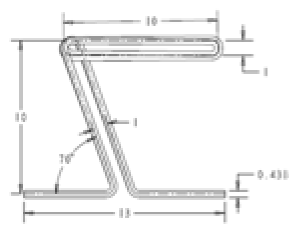
Finite element method offers an ideal method for accurate modeling of the tooth and periodontium with its complicated three-dimensional geometry and makes it possible to analytically apply various force systems at any point and in any direction. This present study would determine the force levels, moment to force ratio and force deflection rate of snail loop, T-loop, Teardrop loop, Teardrop with helix and Opus loop using Finite element method.

Methodology

Twenty five loops were constructed with 0.016×0.022 inch stainless steel wire and 0.017×0.025 inch titanium molybdenum wire. Ansys V15 software was used for creating 3D models. Ansys V15 finite element software was used to construct a three-dimensional model of the retraction loops which are as follows:



Opus



After which forces and moments produced by loop geometries in all three-dimensions were studied.

A computer loaded with IBM consisting of Ansys V15 as the pre and postprocessor and Ansys direct solver which investigated the three-dimensional outcome of individual loops were used in the study.

The horizontal length of all the loop models (distance between the anterior and the posterior node) were kept 13 mm considering the inter-bracket distance from the second premolar midpoint to the canine midpoint considering a first premolar extraction case.

Following 25 FEM models were prepared for the study:

1. Three models for *snail loop* were prepared in 0.017×0.025 inch TMA wire with 0° , 20° α preactivation bends and two models in 0.016×0.022 inch SS wire with 0°,10° α preactivation bends.
2. Three models for *teardrop loop* were prepared in 0.017×0.025 inch TMA wire with 0° ,10°,20° α preactivation bends and two models in 0.016×0.022 inch SS wire with 0°,10° α preactivation bends.

3. Three models for *T- loop* were prepared in 0.017×0.025 inch TMA wire with 0°, 10°, 20° α preactivation bends and two models in 0.016×0.022 inch SS wire with 0°,10° α preactivation bends.

4. Three models for teardrop with *helix loop* were prepared in 0.017×0.025 inch TMA wire with 0°, 10°, 20° α preactivation bends and two models in 0.016×0.022 inch SS wire with 0°, 10° α preactivation bends.

5. Three models for *opus loop* were prepared in 0.017×0.025 inch TMA wire with 0°, 10°, 20° α preactivation bends and two models in 0.016×0.022 inch SS wire with 0°,10° α preactivation bends.

Construction of model in this study was done as follows

Fabrication of the 3D model was done using the 3D modeling software with desired dimensions, prior to the fabrication of finite element model and its analysis.

1. Loops without preactivation bend

A fixed point was determined at the terminal node on the alpha side (corresponding to the canine bracket) on the FEM model. Subsequently the terminal node on the beta side (corresponding to the second premolar bracket) was displaced by a predetermined distance after which the force and the moment produced on the terminal node on the alpha side were recorded on the Ansys software.

2. Loops with preactivation bend

To simulate the engagement of the wire in the brackets a rotation was added to the alpha end until the horizontal leg was completely horizontal and collinear with the bracket slot. The exact displacement at the alpha node was recorded to obtain information about the amount of cross-over produced when the wire was engaged. This point was neutral position for all the loops and starting point for all the activations. Subsequently the terminal node on the beta side was displaced by a predetermined distance after which the force and the moment produced on the terminal node on the alpha side were recorded.

SS wire	Forces produced at D1 and D2 (gm)		Moments produced at D1 and D2 (gm/mm)		M/F ratio at displacement D1 and D2 (mm)		F/D rate at displacement D1 and D2 (gm/mm)
0.016×0.022 inch Preactivation α bend	1mm	2mm	1mm	2mm	1mm	2mm	
0°	219	447	1285	2700	5.87	6.04	223.5
10°	232	471	1063	4136	4.58	8.78	235.5

Table no.1 - Snail Loop- Stainless Steel

Results

Finite element analysis was carried out for different FEM models and code was given to different models prepared, where:

M represents material types (SS)stainless steel wire and (TMA) Titanium molybdenum alloy.

S represents size of wire **(**0.016×0.022 inch as S1 and 0.017 × 0.025 inch as S2).

P represents preactivation angle alpha (zero degree as 0°, ten degrees as 10° for SS wires and , zero degree as 0°, ten degrees as 10°, twenty degrees as 20° for TMA wire). **D** represents displacement, the amount of activation of the given loop model (1 mm as D1 and 2 mm as D2). Total of 25 FEM models were studied to evaluate the M/F ratio, F/D rate and the maximum force generated by the respective loop models after their activation. Results of the study are tabulated as shown in Tables 1 to 10.

TMA wire	Forces produced at D1 and D2 (gm)		Moments produced at D1 and D2 (gm/mm)		M/F ratio at displacement D1 and D2 (mm)		F/D rate at displacement D1 and D2 (gm/mm)
0.017×0.025 inch Preactivation α bend	1mm	2mm	1mm	2mm	1mm	2mm	
0°	118	240	1316	2062	11.15	8.59	120
10°	124	251	1257	1830	10.13	7.29	125.5
20°	130	263	1180	1571	9.07	5.97	131.5

Table no.2 Snail Loop- TMA

SS Wire	Forces produced at D1 and D2 (gm)		Moments produced at D1 and D2 (gm/mm)		M/F ratio at displacement D1 and D2 (mm)		F/D rate at displacement D1 and D2 (gm/mm)
0.016×0.022 inch Preactivation α bend	1mm	2mm	1mm	2mm	1mm	2mm	
0°	318	637	3971	7943	12.48	12.46	318.5
10°	346	693	1153	2307	3.33	3.32	346.5

Table no.3 Teardrop Loop- Stainless Steel

TMA wire	Forces produced at D1 and D2 (gm)		Moments produced at D1 and D2 (gm/mm)		M/F ratio at displacement D1 and D2 (mm)		F/D rate at displacement D1 and D2 (gm/mm)
0.017×0.025 inch Preactivation α bend	1mm	2mm	1mm	2mm	1mm	2mm	
0°	82.9	180	1107	5993	13.35	33.29	90
10°	96	193	2237	6287	23.30	32.57	96.5
20°	103	208	6506	3529	63.16	16.96	104

Table no.4 Teardrop Loop- TMA

SS wire	Forces produced at D1 and D2 (gm)		Moments produced at D1 and D2 (gm/mm)		M/F ratio at displacement D1 and D2 (mm)		F/D rate at displacement D1 and D2 (gm/mm)
0.016×0.022 inch Preactivation α bend	1mm	2mm	1mm	2mm	1mm	2mm	
0°	168	340	952	2067	5.6	6.07	170
10°	182	565	1123	2432	6.17	4.3	282.5

Table no.5 T Loop- Stainless Steel

TMA wire	Forces produced at D1 and D2 gm/mm		Moments produced at D1 and D2 gm/mm		M/F ratio at displacement D1 and D2 gm/mm		F/D rate at displacement D1 and D2 gm/mm
0.017×0.025 inch Preactivation α bend	1mm	2mm	1mm	2mm	1mm	2mm	
0°	92.3	185	2334	3214	25.28	17.37	92.5
10°	99.7	199	1044	8390	10.47	4.47	99.5
20°	108	213	1483	2813	13.73	13.20	106.5

Table no.6 T Loop- TMA

SS wire	Forces produced at D1 and D2 (gm)		Moments produced at D1 and D2 (gm/mm)		M/F ratio at displacement D1 and D2 (mm)		F/D rate at displacement D1 and D2 (gm/mm)
0.016×0.022 inch Preactivation α bend	1mm	2mm	1mm	2mm	1mm	2mm	
0°	144	299	2436	3743	16.91	12.51	149.5
10°	156	322	4638	7952	29.73	24.69	161

Table no.7 Teardrop with Helix Loop- Stainless Steel

TMA wire	Forces produced at D1 and D2 (gm)		Moments produced at D1 and D2 (gm/mm)		M/F ratio at displacement D1 and D2 (mm)		F/D rate at displacement D1 and D2 (gm/mm)
0.017×0.025 inch Preactivation α bend	1mm	2mm	1mm	2mm	1mm	2mm	
0°	79.3	164	1344	2222	16.94	13.57	82
10°	85.3	175	2672	4795	31.32	27.40	87.2
20°	91.7	189	5959	9141	64.98	48.36	94.2

Table no.8 - Teardrop with Helix Loop- TMA

SS wire	Forces produced at D1 and D2 (gm)		Moments produced at D1 and D2 (gm/mm)		M/F ratio at displacement D1 and D2 (mm)		F/D rate at displacement D1 and D2 (gm/mm)
0.016×0.022 inch Preactivation α bend	1mm	2mm	1mm	2mm	1mm	2mm	
0°	37.6	78.2	309	578	8.19	7.3	39.1
10°	39.2	81.7	307	582	8.2	7.13	40.85

Table no.9 - Opus Loop- Stainless Steel

TMA wire	Forces produced at D1 and D2 (gm)		Moments produced at D1 and D2 (gm/mm)		M/F ratio at displacement D1 and D2 (mm)		F/D rate at displacement D1 and D2 (gm/mm)
0.017×0.025 inch Preactivation α bend	1mm	2mm	1mm	2mm	1mm	2mm	
0°	28	58.2	229	428	8.17	7.3	29.1
10°	29	60.5	227	427	7.83	12.9	30.25
20°	30.2	62.8	226	428	7.49	11.9	31.4

Table no.10 Opus Loop- TMA

Discussion

Orthodontic tooth movement is typically characterized as pure translation, pure rotation, or combinations thereof. The ability of a spring to produce a particular displacement depends on delivery of the moment to force ratio. In addition, the load magnitude must be sufficiently high to effect tooth movement without causing injury. For these criteria, the critical spring attributes include a low load deflection rate and a high moment to force ratio.[4, 5]

The tooth movement that occurs is dependent on the moment/force ratio and the quality of the periodontal support: shorter roots or reduced alveolar bone height. This study was designed to optimize the utilization of snail loop by understanding its biomechanical properties and also compare it with T-loop, teardrop with helix, opus, teardrop loop.

Mathematical approach and experimental methods are routinely used for analyzing M/F ratio and F/D rate of loop designs.[6,7] Laser holography,[8] photoelastic models/typodont[7] are various experimental approaches that routinely utilized by clinicians for extensive analysis of retraction loops. Since the above mentioned experimental approaches are time consuming and expensive, presently finite element method (FEM) is observed to be used extensively to study loop designs.

Based on the dimensions prescribed by the respective authors a total of twenty five FEM models were constructed. The horizontal length of all the loop models (distance between the anterior and the posterior node) were kept 13 mm considering the interbracket distance from the second premolar midpoint to the canine midpoint considering a first premolar extraction case. Titanium molybdenum alloy (TMA) and stainless steel (SS) are the most commonly used wires for making loops. Stainless steel wires have a range of values both for elasticity and yield strength related to the change in different parameters at their production stage such as freezing and incandescence during cold working. They produce higher forces applied during shorter time periods since they have lower spring back ability and also store less energy compared to those of beta-titanium or nickel-titanium.[5]

The cross-sectional area of stainless steel orthodontic wire (0.016 x 0.022 inch) was then calculated. The Young's modulus of the stainless steel wire was assumed to be 200 Gpa and the Poisson ratio was equal to 0.3. The boundary conditions were ascertained so that the terminal node in the alpha segment (anterior) was restrained (i.e. it was not able to move in the X, Y or Z axes, and it was not able to rotate around these axes). Similar to the alpha segment, the beta segment was retrained except that the terminal node of beta segment was free to move along the horizontal leg. This movement simulated the wire sliding distally through a molar tube. The first step was to determine the forces, moments and the M/F ratios of each loop. Similarly was done for 0.017 inch x 0.025 TMA wire , the Young's modulus of the TMA wire was assumed to 80 Gpa and the Poisson ratio was equal to 0.3.

Titanium molybdenum wires were introduced in 1979 as an orthodontic wire.[6] Modulus of elasticity of these wires is lower than half of stainless steel wires and almost twice that of Nitinol.[7-8] These wires demonstrate good formability, but should not be strongly bent as there is a risk of breaking. Electrical welding of biomechanical attachments is possible, but overheating should not be done as it makes the wire more brittle.

According to a recent study, beta-titanium wires are better in terms of join-ability than stainless steel wires since they demonstrate higher resilience and better surface and structural characteristics, which indicates only a minor change in wire properties after welding.[9]

Most of the loop mechanics advocate full slot engagement and most often preferred wire dimension is 0.017× 0.025 inch and 0.016 × 0.022 inch wire dimensions. Any variation in the material of wire produces a different F/D rate. Hence we chose both TMA and SS wires of 0.017 × 0.025 inch and 0.016 × 0.022 inch wire dimensions respectively.

It was observed that the forces, moments and F/D rate produced from SS dental arch wire was nearly twice in comparison to TMA where at 0° and 10° SS wire teardrop and opus loop produced optimum force after D1 displacement and higher force after D2 displacement. Least force was generated by opus loop after D1 and D2 displacements (Table no.3 and 9) and by TMA, snail loop produced optimum force after D2 displacement and least force was generated by opus loop after D1 and D2 displacements at 0°,10° and 20° of pre activation bends(Table no.2 and 10). Higher force was observed by stainless steel wire as compared to TMA wire these could be because of higher modulus of elasticity of SS wire as compared to TMA which is almost half of it. A force recommended for incisor retraction on each side is 100 gm.[9]

It was observed that M/F ratio produced by opus loop in SS wire at 0° and 10° and TMA wire at 0° after displacement of D1 was optimum for translatory movement but maximum force generated by opus loop is least as compared to other loops. As height of opus is more this could contribute for increase in M/F ratio (Table no.10 and 11).

The inherent M/F ratio produced by snail loop is not adequate to impart translatory movement of the dentition at 0°, so to increase the M/F ratio gable/preactivation bends have to be incorporated into the loop. Snail loop prepared in TMA archwire with preactivation bends after D1 and D2 displacement and with SS wire after giving 10° of preactivation bend and D2 displacement produced optimum M/F ratio for bodily movement (Table no.1 and 2). Reason for such an observation could be attributed to various physical properties exhibited by TMA wire.[9]

M/F ratio and LDR defines the mechanical properties of the loop. Thus large activation may change the LDR and M/F ratio as a result of changed shape of the spring.

It was observed that maximum F/D rate produced was with snail loop in TMA wire and teardrop loop in SS wire but on comparison between TMA and SS wires, TMA wires produced least F/D rate. F/D rate and maximum force generated of opus loop is the lowest compared to other loops (Table no.9 and 10). Configuration of the opus loop and 70° angulation given to its vertical leg during optimization of the design could be attributed to such an observation.

However, certain shortcomings such as could not be overcome; the effect of friction and play of the wire in the bracket slot was not studied. In order to study these, special elements, known as gap elements would have to be employed. The use of these would have made the problem extremely complex. Overall, the FEM results allow us to study the forces, moments, displacements and stresses only when the wire is engaged into the bracket. We were not able to study the changes in the force system or the stress patterns as the wire deactivates, or as the tooth moves under the influence of the forces. Forces and moments were studied for only mesio-distal movement of the teeth. Involving the forces and moments for buccolingual and occluso-gingival would have made the problem more complex, however it leaves scope for further studies. The role of friction, play and sliding of the archwire in the slot can be studied. Variations of slot sizes and wire sizes, and their effect on the forces and moments, variations of the archwire materials used to fabricate the loops, and their effect on the forces and moments can also be studied. The effects of forces and moments generated by the recommended loop-archwire combinations can also be studied for the stresses generated at the teeth and periodontium.

Conclusion

In this present study after evaluating and comparing all the characteristics of the mentioned loops, we observed that snail loop has a definite advantage over teardrop loop, T loop, Teardrop with helix and opus loop in all respects of biomechanical characters. Snail loop with incorporation of gable bends is very efficient to deliver M/F ratio though opus loop deliver efficient M/F ratio but force generated is least amongst all the loops.

Finer shape morphology of snail loop provides ease of fabrication and prevents tissue impingement which is a drawback of opus loop where the increased height of the loop can create problem of tissue impingement and reduce patient compliance.

For optimum delivery of M/F ratio using snail loop must be prepared in either 0.016×0.022 SS wire with preactivation bend of 10° after D2 displacement or 0.017×0.025 TMA wire with preactivation bend of 10° and 20° after D1 displacement. No matter how precise we try to conduct our study we cannot specifically simulate and construct an artificial oral environment to conduct a study. Hence, a further assessment on the clinical efficiency and ease of use of snail loop on patients has to be conducted.

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