Comparative Assessment of Torque Expression of Stainless Steel, Nickel Titanium, Heat Activated Nickel Titanium and Titanium Molybdenum Alloy Wires - A Finite Element Method Study

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Abstract

Objective: To assess and compare the torque values of different wires - Stainless Steel, Nickel Titanium, Heat Activated Nickel Titanium and Titanium Molybdenum alloy using Finite Element Analysis.

Methods: Three-dimensional model of a maxillary right central incisor tooth was made with the surrounding periodontal ligament and alveolar bone. Three dimensional CAD models of a MBT 0.022'' slot bracket, 8mm long 0.019x0.025" and 0.021x0.025" orthodontic wires were also made using the CATIA V5 R21 software. After the models were meshed with the Hyper mesh software, mechanical properties such as Young's modulus and Poisson's ratio of tooth, compact bone, spongy bone, periodontal ligament, Stainless Steel, NiTi, HANT and TMA wires were assigned to the finite element model. The torques expressed in the central incisor by the different arch wires were recorded using ABAQUS 6.14 FEM software.

Results: The finite element analysis indicated that for each of the four different type of materials , stainless steel wire produced the highest angular displacement followed by TMA, then NiTi and HANT when it was placed in the 0.022" slot bracket for both 0.019x0.025" and 0.021x0.025" wires. 0.019x0.025" stainless steel expressed the highest angular displacement of 1.2456° in the 0.22" slot bracket whereas 0.019x0.025" TMA displayed an angular displacement of 1.2450°, 0.019x0.025" NiTi 1.1996° and 0.019x0.025" HANT 1.1207° when engaged in 0.022" bracket slot. The angular displacement of a 0.021x.025"SS wire when placed in 0.022" slot bracket is 1.4560° which is the highest when compared to TMA, NiTi and HANT wires of the same dimension. HANT wire showed the least angular displacement of 1. 2262° when compared to TMA and NiTi which showed an angular displacement of 1.4074° and 1.3352° respectively.

Conclusion: According to the result of this finite element study, Stainless steel yielded the largest torque expression, followed by TMA and NiTi and then HANT.

Key words: Finite Element Method (FEM), HANT, NiTi, Stainless Steel, Torque expression, TMA.

Introduction

The moment generated when a rectangular wire twists in the bracket slot is described as torque. The arch wire moves the root in a buccolingual direction due to the induced torsional load depending on the play of the wire in the bracket slot, quantity of torsion, the angulation, the dimension and material of the wire and the disfiguration of the bracket.[1]

Torque is nothing but the torsion of the rectangular wire. Torque can be- (1) passive torque, which has no definite action on the tooth when engaged, and (2) active torque, which has a definite action on the tooth when engaged. Torque force can be either 1) lingual torque, which shows a tendency to tip the roots labially and the crown lingually, or 2) labial/buccal torque, which tends to tip the crown of the tooth labially or buccally and the roots lingually according to the action upon the tooth crown. [2]

The torque expression is depended on the amount of play between the bracket slot and the arch wire and by variations in tooth anatomy, in bracket placement, inaccuracy in the bracket slot and arch wire dimensions, mode of ligation, and stiffness of the archwire,[3] bracket deformation, magnitude of wire torsion and dimension, bracket design, and wire edge beveling.

Maxillary incisor torque is critical in achieving an ideal smile line, a perfect Class I relationship, correct anterior guidance, and under torqued anterior teeth can prevent the distal movement of the anterior maxillary dentition.

The minimum torque moment required to produce clinically effective torque is not identified at this time unfortunately. It would be useful to know the amount of torque expressed that is clinically significant for commonly used wire alloys such as Stainless Steel, Nickel Titanium, Titanium Molybdenum Alloy and Copper Nickel Titanium.

The relative involvement of wire type to torque expression has not been well defined. Nickel titanium (NiTi) Alloys, which has a low modulus of elasticity; express decreased torque relative to stainless steel. Alloys with reduced modulus such as CuNiTi and beta-titanium (β-Ti), with only a portion of the stiffness of stainless steel wire, may be futile in yielding a torque moment in the bracket slot.[4]

The finite element method (FEM) is an excellent engineering tool to study problems of this nature. Its precision in analyzing the strains and stresses in objects such as an arch wire is very elevated when it is provided with precise material properties, loads and structural configuration.

Hence, the purpose of this study is to compare and assess the torque expression between four commonly employed wire alloys: Stainless Steel, Nickel Titanium, Heat Activated Nickel Titanium and Titanium Molybdenum Alloys using Finite Element Analysis.

Materials

The study was done using a three dimensional finite element analysis using a

1. Workstation computer with the following configuration
   a. Intel(R) Xeon(R) CPU E5-26090@2.40GHz
   b. 256GB RAM
   c. Graphic card-NVIDIA Quadro 4000
   d. Color monitor 24"
   e. Optical mouse
2. D models of
   a. Maxillary right central incisor with periodontal ligament and alveolar bone
   b. MBT 0.022'' slot bracket
   c. 0.019x0.025" Stainless Steel, Nickel Titanium, Heat Activated Nickel Titanium and Titanium Molybdenum Alloy wires
   d. 0.021X0.025" Stainless Steel, Nickel Titanium, Heat Activated Nickel Titanium and Titanium Molybdenum Alloy wires
3. Software used
   a. CATIA V5 R21 is used for CAD modeling
   b. Hyper mesh V12.0 is used for Finite Element Modeling
   c. ABAQUS 6.14 is used for Finite Element Analysis.

Methodology

Three-dimensional (3D) models of a maxillary right central incisor tooth was made with the surrounding periodontal ligament and alveolar bone (Fig. 1). Three dimensional CAD models of a maxillary right central incisor tooth with MBT 0.022'' slot bracket (Fig. 2), 8mm long 0.019x0.025" and 0.021x0.025" orthodontic wire engaged in the MBT 0.022" slot bracket were created using CATIA V5 R21 software as shown in Figure 3 and 4 respectively.

Construction of the Finite Element Model: In particular 4 noded 3D tetrahedral elements were used for discretizing the complete assembly. Fine mesh was used where highly complex and intricate geometry needs to be captured.

Second order tetrahedral elements are used for discretizing the bone, crown, root, bracket, wire and ligament. A total of 52110 nodes and 265436 elements were used for the 0.019X0.025" orthodontic wire and 52198 nodes and 265928 elements have been used for the 0.021X0.025" orthodontic wire for discretizing the model completely. Figure 5, shows the finite element model thus created and was used for analysis in the study.

Meshing (Checking the mesh quality): Mesh quality is an important criterion to obtain accurate results. So, quality check was done which includes check for skewness, aspect ratio and jacobian values. Any elements that failed the requirements for appropriate skewness and aspect ratio were cleaned up. The process was repeated to obtain the best quality mesh for further analysis. The final finite element model (Figure6) thus built comprised of a total of 52110 nodes and 265436 elements for the 0.019X 0.025" orthodontic wire and 52198 nodes and 265928 elements for the 0.021X0.025" orthodontic wire.

Assigning Properties to the various structures of the Finite element Model: Mechanical properties such as Young's modulus and Poisson's ratio of tooth, compact bone, spongy bone, periodontal ligament, Stainless Steel, NiTi, HANT and TMA orthodontic wires were assigned to the finite element model. Table 1 shows the mechanical properties (linear elastic properties) used for different components that form the finite element model.

Table 1: Elastic Modulus and Poisson's Ratio of Various Materials Used in the Study

Material	Elastic modulus(E) (Mpa)	Poisson's Ratio($_v$)
Tooth	2000	0.15
Compact bone	13800	0.2
Spongy bone	345	0.3
Periodontal ligament	50	0.4
Stainless Steel	160000	0.3
NiTi	34000	0.3
HANT	47760	0.3
TMA	62000	0.3

Applying Constraints: After meshing of the model, mechanical properties, boundary conditions or constraints were applied on to the finite element model. Fig. 7 shows the base of the bone constrained. In particular, few nodes were selected around the base of the bone and Single Point Constraints (SPC) were applied.

Application of Load and analysis: After applying a load of 234.5g and applying the constraints (Figure 8), ABAQUS 6.14 was used for Finite Element Analysis. An ABAQUS solver deck was exported in .inp format from Hyper mesh which comprises of element ID, property ID, loads and constraints data required to represent each element in finite element model. The solver deck was then imported to ABAQUS solver. After solving, a results file was created. This output file was read in Hyper view which is a post-processing software.

The results were represented graphically and tabulated.

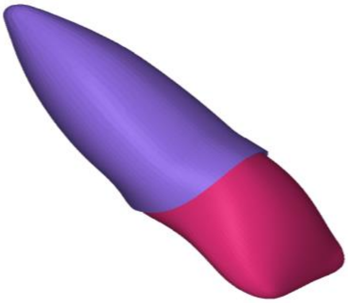


Fig. 1: 3D CAD model of maxillary central incisor and periodontal ligament

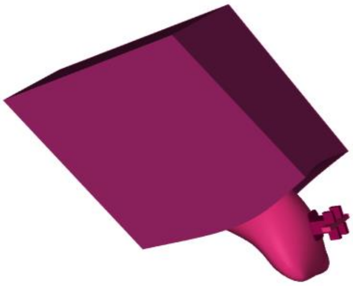


Fig. 2: 3D CAD model of maxillary central incisor with MBT 0.022”slot bracket and orthodontic wire

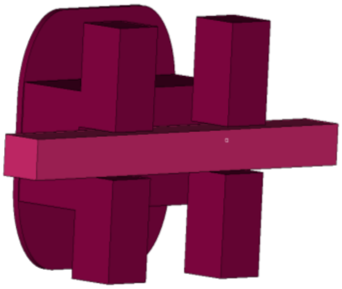


Fig. 3: 3D CAD model of 0.019X0.025” orthodontic arch wire in a 0.022” slot bracket

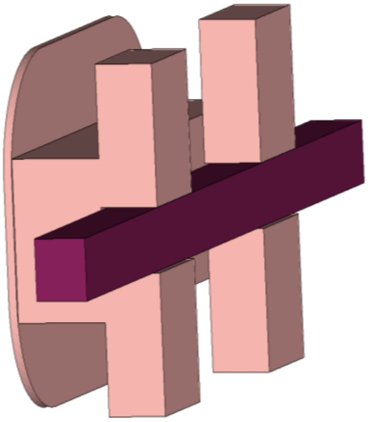


Fig. 4: 3D CAD model of 0.021X.025” orthodontic arch wire in a 0.022” slot bracket

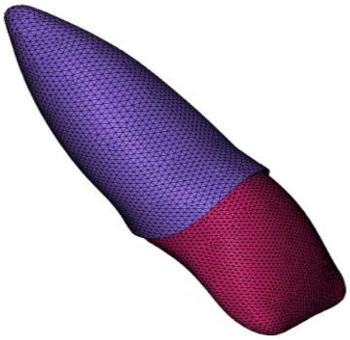


Fig. 5: Finite Element Model of the maxillary central incisor tooth with periodontal ligament

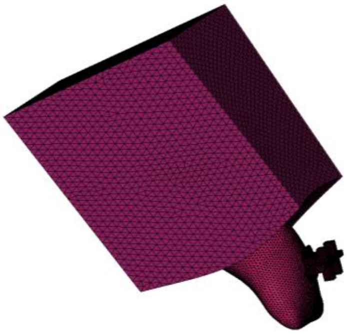


Fig. 6: Hypermesh model of maxillary central incisor with MBT 0.022”slot bracket and orthodontic wire

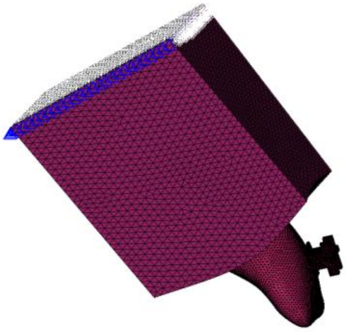


Figure 7: Constraints applied on the Finite Element Model

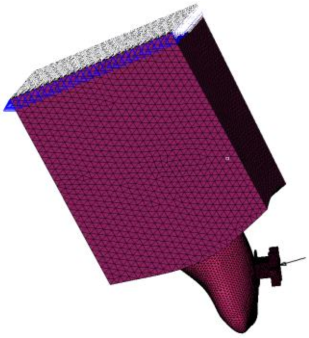


Figure 8: Application of Load

Results

Graphs I and II shows plotted comparisons of the angular displacements for different orthodontic arch wires like SS, TMA, NiTi and HANT for 0.019x0.025" and 0.021x0.025" dimensions respectively.

For each of the four different type of materials, stainless steel wire produced the highest angular displacement followed by TMA, then NiTi and HANT when it was placed in the 0.022" slot bracket for both 0.019x0.025" wire and 0.021x0.025" wire. Stainless Steel expressed the highest angular displacement of 1.2456° in the 0.22" slot bracket when it had a dimension of 0.019x0.025",whereas TMA displayed an angular displacement of 1.2450°, NiTi 1.1996° and HANT 1.1207° with 0.019x0.025" dimension when engaged in 0.022" bracket slot as shown in Table 2.

The angular displacement of a 0.021x.025"SS wire when placed in 0.022" slot bracket is 1.4560° which is the highest when compared to TMA, NiTi and HANT wires of the same dimension. HANT wire showed the least angular displacement of 1. 2262° when compared to TMA and NiTi which showed an angular displacement of 1.4074° and 1.3352° respectively. This is tabulated in Table 3.

Graphs III,IV,V and VI compares the angular displacements between 0.019x0.025" and 0.021x0.025" dimension wires of HANT, NiTi, TMA and SS respectively ,in a 0.022" slot bracket, which shows more angular displacement of the 0.019x0.025" wire than 0.021x0.025"wire.

Graph I: Comparison Bar Graph Showing Angular Displacements for Different Type of Materials in 0.019x0.025"dimension

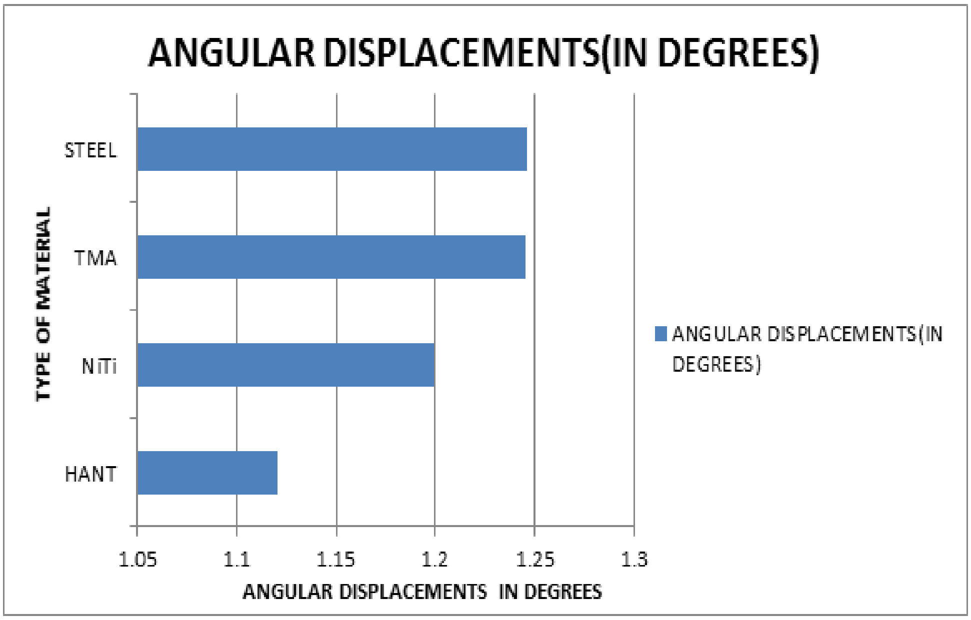


Table 2: Angular Displacements for Different Type of Materials in 0.019x0.025"dimension

Sl. No	Material	Angular Displacements(In Degrees)
1.	HANT	1.1207
2.	NiTi	1.1996
3.	TMA	1.2450
4.	SS	1.2456

Graph II: Comparison Bar Graph Showing Angular Displacements for Different Type of Materials in 0.021x0.025"dimension

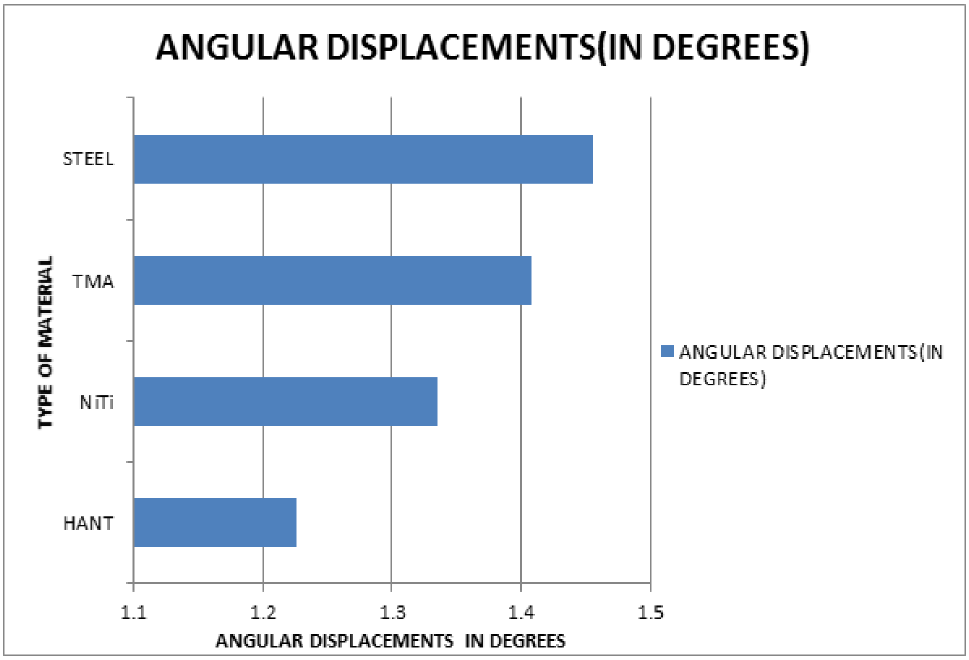
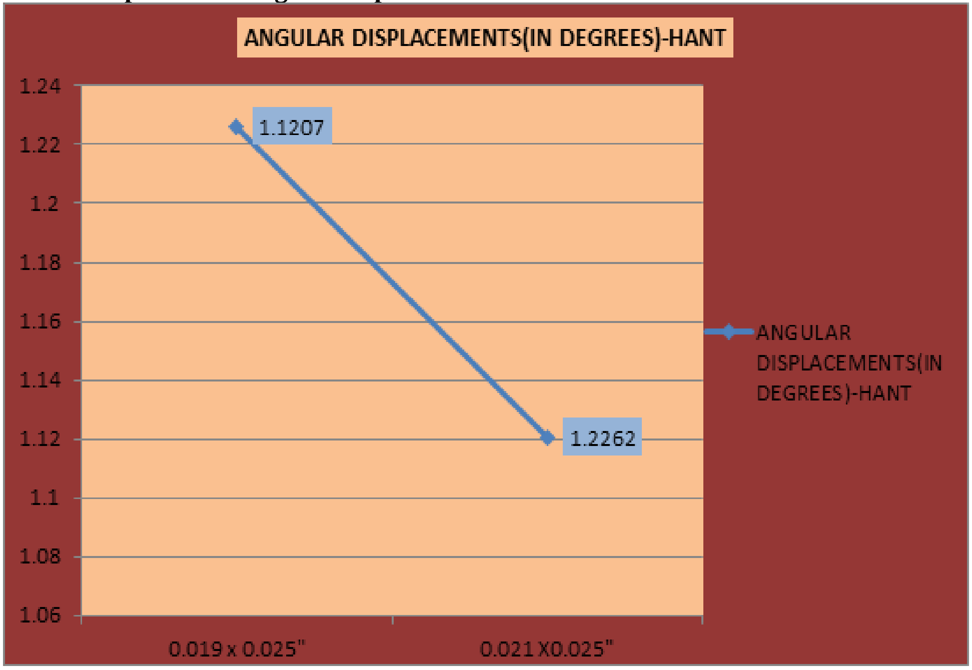


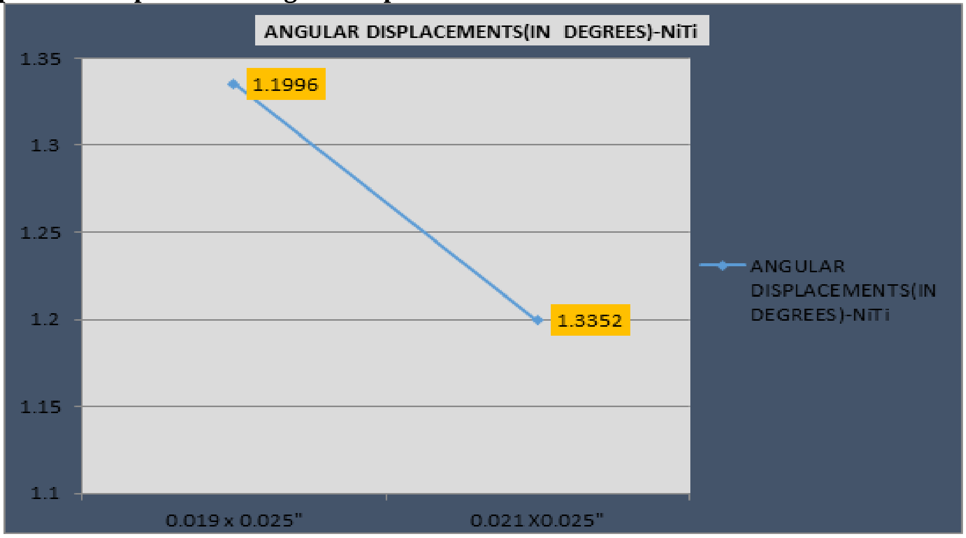
Table 3: Angular Displacements for Different Type of Materials in 0.021x0.025"dimension

Sl. No	Material	Angular Displacements(In Degrees)
1.	HANT	1.2262
2.	NiTi	1.3352
3.	TMA	1.4074
4.	SS	1.4560

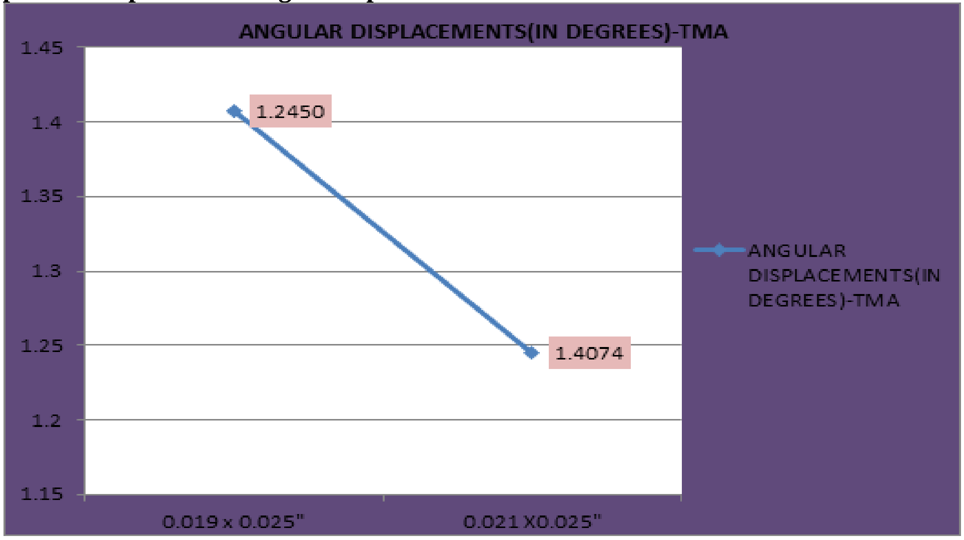
Graph III: Comparison of angular displacement for 0.019x0.025" and 0.021x0.025" HANT wire



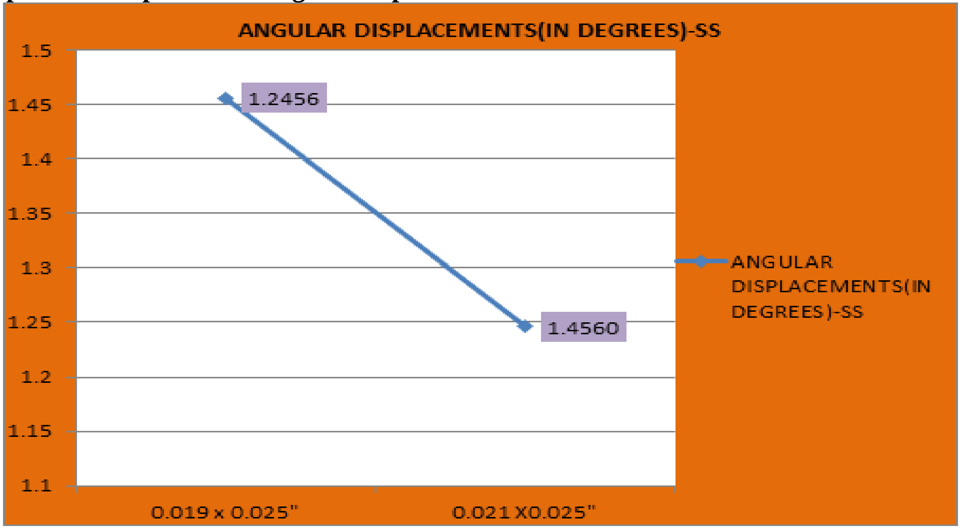
Graph IV: Comparison of angular displacement for 0.019x0.025" and 0.021x0.025" NiTi wire



Graph V: Comparison of angula displacement for 0.019x0.025" and 0.021x0.025" TMA wire



Graph VI: Comparison of angular displacement for 0.019x0.025" and 0.021x0.025" SS wire



Discussion

The main objective in the field of orthodontics is to create an ideal smile and occlusion. This target is achieved by the movement of teeth in the alveolar bone. In the treatment of malocclusions in Orthodontics, expressing the proper torque poses a difficult challenge. In Orthodontics, torque represents the buccopalatal crown/root inclination of a tooth.[5] The torque control over the roots of all the teeth is an important phase in the treatment planning. The control over the root torque of the maxillary incisor permits an optimal inter-incisal angle, adequate incisor contact and sagittal alteration of the dentition in order to achieve perfect intercuspation.[6]

The amount of torquing moments produced by arch wires in various materials and dimensions need to be anticipated, because it is suggested that excess torquing moments may damage the roots or the cortical plates.[1] As the typical arch wire is too stiff to engage all the bracket slots, there will be a crisis of initiating torque control at the beginning of treatment. With the advent of pretorqued brackets as in the pre-adjusted straight wire appliance, root control is obtained by means of rectangular wires. A rectangular or square wire that nearly fills the bracket slot is essential for initial wire leveling and torque control. As the bracket slot fills on increasing the thickness of the archwire, the wire's flexibility and the elastic range decreases.[7]Alloys such as Nickel Titanium (NiTi), with a low modulus of elasticity result in decreased torque expression relative to stainless steel.

A study conducted by Amy Archambault et al suggested that reduced modulus of alloys such as NiTi and beta-titanium (β-Ti) with only a fraction of the stiffness of stainless steel wire may not be very effective in transmitting a torque moment within a bracket slot. The relative role of untwisted wire material to torque expression is not well defined. Hence, the purpose of the present descriptive study is to evaluate the potential of untwisted rectangular wires of different dimension and material type to control torque. The study simulated the situation occurring when the torque is applied by 0.019x0.025" and 0.021x0.025" rectangular wires of four different commonly used material types namely: Stainless Steel, Nickel Titanium, Heat Activated Nickel Titanium and Titanium Molybdenum Alloy and the study is limited to the torque expressed by an individual central incisor.

Stainless steel has traditionally been the wire alloy of choice for torque application; however, β-titanium and nickel titanium or copper nickel titanium are also currently being employed for this purpose.

Stainless steel arch wires, which replaced the gold alloys which had been used for orthodontics up until that time, were developed after World War I.[8] A typical combination of 18% chromium and 8% nickel is used in orthodontics nowadays in a formulation is known as 18-8 stainless steel.[9] These wires exhibit low coefficient of friction and are relatively stiff. Stainless steel has less elasticity than TMA and NiTi. When activated in bending or torsion, stainless steel is capable of storing less energy. This implies that stainless steel wires have a steep load deflection, i.e., the forces delivered by the SS wires dissipate over a very short amount of deactivation, thereby, requiring more frequent activations.[10]

Dr. Burstone introduced the Beta-titanium (β-Ti) archwires in 1980 as he wanted to produce an alloy with deactivation characteristics less than half that of stainless steel and twice that of martensitic stabilized nitinol.[11] Beta-phase titanium alloys contain approximately 80% titanium, 11.5% molybdenum, 6% zirconium, and 4.5% tin. Subsequently, Ormco developed a low-stiffness beta-phase titanium-molybdenum-alloy called TMA®. In comparison with Nitinol, TMA was smoother and had good weld ability and formability. In comparison with stainless steel, TMA produced gentle, linear forces with greater elastic range. These characteristics made it an ideal arch wire in many ways, though its high coefficient of friction and consequent inability to allow sliding of teeth were a drawback for space closure.[8]

Its spring back is superior to that of stainless steel allowing it to be deflected twice as far as stainless steel without permanent deformation. These wires deliver approximately half the force of stainless steel wires.[12]

Nitinol was developed by William F Beuhler, a research metallurgist for a space programme. Nickel titanium archwires were introduced in 1972 under the brand name Nitinol™ (Nickel Titanium Naval Ordinance Laboratory). Nitinol was a stabilized martensitic alloy with a low force per unit of deactivation (low stiffness)[8] that delivered only one quarter of force per unit area of deactivation of stainless steel.[13] Nitinol has unique characteristics of low stiffness, high reversibility and excellent spring back property.

Copper NiTi was introduced in USA by Rohit Sachdeva and Suchio Miuasaki in 1994.The addition of copper to NiTi alloys lowers rigidity and thus reduces activation and deactivation moments.[14]

Strength is a material property independent of cross sectional shape or length; however, stiffness and range are affected by a change in wire geometry. The performance of an arch wire depends on a combination of material properties and geometric factors. Shear stress, rather than bending stress, results from torsion of an arch wire. Decreasing the size of a wire decreases its flexural rigidity and increases its range in torsion.[9]

Torsional stiffness determines how a material will behave in torsion. Torsional stiffness depends on the shear modulus of the material, the polar moment of inertia and the length of the beam. The shear modulus of an arch wire depends on the alloy. Stainless steel possesses almost twice the torsional stiffness of β-Ti[8] and 4 times that of NiTi.[13]

Actually, the arch wire stiffness can alter the variations of the loads arising from the activation of a wire engaged to the pre-adjusted slot. In the case of Ni-Ti which is a low-modulus alloy, the torque expression is decreased more because some activation is dissipated due to elastic deformation.[7]

It is postulated that the clinical efficiency of low-modulus wires in delivering torque is questionable if no wire twisting is incorporated where this is applicable, i.e., in β-Ti wires. In addition, some thoughts has been expressed in the past regarding the ability of HANT wires to transfer the required moment because of a decrease in the expression of load during consumption of cold beverages. The intake of cold drinks reverses the transformation from the austenitic phase to the martensitic phase. Studies has suggested that this effect reduces the stiffness upto 50% at least upto 2 hours; which adversely affects the torque expression of the pre-adjusted bracket.[7]

The FE method enables us to answer complex biomechanical questions in the field of orthodontics via simulation; moreover, it enables investigators to predict the behaviour of biological structures in many specific situations.

In the present study, finite element models of a maxillary right central incisor tooth with a MBT 0.022'' slot bracket, 0.019x0.025" and 0.021X0.025" orthodontic wire each made of Stainless Steel, Nickel Titanium, Heat Activated Nickel Titanium and Titanium Molybdenum Alloy were made using the Hyper mesh V12.0. The base of bone was constrained and a frictional force of 234.5g [15] was applied. The angular displacement in the central incisor by the different arch wires were recorded using ABAQUS 6.14 FEM software .An ABAQUS solver deck was exported in .inp format from Hyper mesh which comprises of element ID, property ID, loads and constraints data required to represent each element in finite element model. The solver deck was then imported to ABAQUS solver. After solving, a results file was created. This output file was read in Hyper view which is post-processing software.

Table 2 and 3 shows the angular displacement expressed by the orthodontic arch wires of different type of materials of 0.019x0.025" and 0.021x0.025" dimension, when engaged in 0.022" slot bracket respectively. In the present study, angular displacement stands for the torque expressed. In our study, stainless steel expressed the maximum angular displacement, compared to TMA and NiTi. Similar studies were conducted in the past which showed similar results.[6,7,35]

HANT wire displayed the least angular displacement compared to SS, TMA and NiTi as shown in graphs I and II due to its reduced stiffness. No similar studies were conducted in the past for the comparison of torque expression of SS, TMA, NiTi and HANT with untwisted rectangular wire using FEM study.

Also, the 0.021x0.025" wires expressed more angular displacement than the 0.019x0.025" wires of the same material as shown in Graphs III, IV, V and VI.

Limitations of this Study & Scope for further Studies

Since this study was simulated digitally using advanced computer software, it performed short of an exact picture of the scenario *in vivo*. The results attained by this *in silico* study needs to be confirmed by *in vivo* studies before they can be applied to clinical practice. As the tooth is modeled to be pinned to the supporting bone, it is considered as a rigid unit and the nodes that connect the tooth to the bone is considered fixed. This assumption will introduce some error .The progress in such FEA will be limited until more defined physical properties for enamel, dentin , periodontal ligament, cancellous and cortical bone are available. Therefore, although the present findings are a useful guide to the anticipated clinical behavior of the different materials of wires used in the field of Orthodontics, the observed clinical behavior may differ as the bone density and tooth morphology varies from person to person. This would help to determine whether the results of this study are comparable to what might be seen on a clinical situation.

Conclusion

The objective of this study was to identify differences in torque expression between stainless steel, TMA, HANT and NiTi wire. According to this finite element analysis, the following conclusions can be made:

1. Stainless steel expressed the highest torque, followed by β-titanium and then by NiTi and HANT.
2. 0.019x0.025"SS wires expressed the highest torque when compared to TMA, NiTi and HANT wires of the same dimension when engaged in 0.022" bracket slot.
3. 0.021x0.025"SS wires expressed the highest torque when compared to TMA, NiTi and HANT wires of the same dimension when engaged in 0.022" bracket slot.
4. HANT wire expressed the least torque compared to SS, TMA and NiTi wires.
5. 0.021x0.025"SS wires expressed more torque compared to 0.019x0.025"SS wires when engaged in 0.022" slot bracket.

The conclusion drawn at the end of the study is

1. Stiffer the arch wire, greater the torque expressed.
2. Thicker the dimension of arch wire in the slot, greater the torque expressed.

Conflict of Interest: None

Source of Support: Nil

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