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THE EFFECT OF MOLAR UPRIGHTING SPRING LENGTH ON FORCE SYSTEMS GENERATED BY NICKEL-TITANIUM SPRINGS

O EFEITO DO COMPRIMENTO DA MOLA DE VERTICALIZAÇÃO MOLAR NOS SISTEMAS DE FORÇAS GERADOS POR MOLAS DE NÍQUEL-TITÂNIO

EL EFECTO DE LA LONGITUD DEL RESORTE DE VERTICALIZACIÓN MOLAR EN LOS SISTEMAS DE FUERZAS GENERADOS POR RESORTES DE NÍQUEL-TITANIO

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ABSTRACT
This study evaluated the force system generated by the Memory Titanol Spring (MTS) with different nickel-titanium segment lengths for molar uprighting using an orthodontic force tester (OFT). The springs were activated at 30° in the posterior segment (β) and divided into four groups (G0, G1, G2, G3). The nickel-titanium and steel connection were fixed at 0 mm, 1 mm, 2 mm, and 3 mm from the molar auxiliary tube curvature. Each group had five MTS, with steel measuring 0.017" by 0.022" and nickel-titanium 0.018" by 0.025". Molars showed extrusion in all groups, with mean values of -0.54 N (G0), -0.68 N (G1), -0.66 N (G2), and -0.66 N (G3). The anterior reacting unit showed mandibular premolar intrusion from 0.56 N (G0, G2) to 0.67 N (G3). Uprighting moments (Ty) of the molars indicated distal moments of 17.62 N·mm (G0), 16.47 N·mm (G1), 16.58 N·mm (G2), and 14.76 N·mm (G3). Distal premolar moments were 1.49 N·mm (G0), 2.63 N·mm (G1), 2.44 N·mm (G2), and 2.42 N·mm (G3). Nickel-titanium segment length showed statistical differences. All pre-activations generated molar extrusion and premolar intrusion at low intensity. G0 was most favorable for molar uprighting. All groups showed low-intensity distal moments on the anterior anchorage side, likely sub-optimal.

Keywords: Orthodontic. Biomechanics. Materials. Forces. Tipping.

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RESUMO
Este estudo avaliou o sistema de forças gerado pela Mola de Titânio com Memória (Memory Titanol Spring – MTS) com diferentes comprimentos de segmento de níquel-titânio para a verticalização de molares, utilizando um testador de forças ortodônticas (Orthodontic Force Tester – OFT). As molas foram ativadas a 30° no segmento posterior (β) e divididas em quatro grupos (G0, G1, G2, G3). A conexão entre o níquel-titânio e o aço foi fixada a 0 mm, 1 mm, 2 mm e 3 mm da curvatura do tubo auxiliar do molar. Cada grupo foi composto por cinco MTS, com o segmento de aço medindo 0,017" × 0,022" e o de níquel-titânio 0,018" × 0,025". Os molares apresentaram extrusão em todos os grupos, com valores médios de -0,54 N (G0), -0,68 N (G1), -0,66 N (G2) e -0,66 N (G3). A unidade reativa anterior apresentou intrusão dos pré-molares mandibulares variando de 0,56 N (G0, G2) a 0,67 N (G3). Os momentos de verticalização (Ty) dos molares indicaram momentos distais de 17,62 N·mm (G0), 16,47 N·mm (G1), 16,58 N·mm (G2) e 14,76 N·mm (G3). Os momentos distais nos pré-molares foram de 1,49 N·mm (G0), 2,63 N·mm (G1), 2,44 N·mm (G2) e 2,42 N·mm (G3). O comprimento do segmento de níquel-titânio apresentou diferenças estatisticamente significativas. Todas as pré-ativações geraram extrusão molar e intrusão dos pré-molares em baixa intensidade. O grupo G0 mostrou-se o mais favorável para a verticalização molar. Todos os grupos apresentaram momentos distais de baixa intensidade no lado da ancoragem anterior, provavelmente subótimos.

Palavras-chave: Ortodontia. Biomecânica. Materiais. Forças. Inclinação.

RESUMEN
Este estudio evaluó el sistema de fuerzas generado por el Memory Titanol Spring (MTS) con diferentes longitudes de segmento de níquel-titanio para la verticalización de molares, utilizando un probador de fuerzas ortodónticas (Orthodontic Force Tester – OFT). Los resortes se activaron a 30° en el segmento posterior (β) y se dividieron en cuatro grupos (G0, G1, G2, G3). La conexión entre el níquel-titanio y el acero se fijó a 0 mm, 1 mm, 2 mm y 3 mm de la curvatura del tubo auxiliar del molar. Cada grupo estuvo compuesto por cinco MTS, con acero de 0,017" × 0,022" y níquel-titanio de 0,018" × 0,025". Los molares presentaron extrusión en todos los grupos, con valores medios de -0,54 N (G0), -0,68 N (G1), -0,66 N (G2) y -0,66 N (G3). La unidad reactiva anterior mostró intrusión de los premolares mandibulares, variando de 0,56 N (G0, G2) a 0,67 N (G3). Los momentos de verticalización (Ty) de los molares indicaron momentos distales de 17,62 N·mm (G0), 16,47 N·mm (G1), 16,58 N·mm (G2) y 14,76 N·mm (G3). Los momentos distales en los premolares fueron de 1,49 N·mm (G0), 2,63 N·mm (G1), 2,44 N·mm (G2) y 2,42 N·mm (G3). La longitud del segmento de níquel-titanio mostró diferencias estadísticamente significativas. Todas las preactivaciones generaron extrusión molar e intrusión de premolares de baja intensidad. El grupo G0 fue el más favorable para la verticalización molar. Todos los grupos mostraron momentos distales de baja intensidad en el lado de la anclaje anterior, probablemente subóptimos.

Palabras clave: Ortodoncia. Biomecánica. Materiales. Fuerzas. Inclinación.

1 INTRODUCTION

It is very common for adult patients to lose their first permanent molars. As a result, the lower second molars tilt mesially.[1] There are several mechanical techniques available for uprighting the lower molars, the most common of which are the Segmented Arch Technique (SAT)[2] and continuous wire mechanics.[3]

Sander and Wichelhaus propose a prefabricated spring called Memory Titanol Spring (MTS)[4] and describe three systems of forces generated by activations, including (1) upright plus molar intrusion, (2) upright plus extrusion, and (3) upright with root movement.[5]

In the literature, a single study reports on the system of forces produced by wires with "V" bends through a mathematical analysis of deflection. Using six geometries, the authors examined the different inter-bracket relationships. The mid-distal positioning of the V-bend is crucial for establishing the system of forces and moments. A central bend generates moments of equal intensity and opposite directions. As the bend is moved away from the center, predictable combinations of moments and forces are created, known as asymmetrical "V" bends.[6] However, no published study has described the system of forces generated by MTS using different lengths of the nickel-titanium segment in molar uprighting. A combination of wires with different load/deflection ratios can result in varying force systems, and activations based on the geometries described by Burstone may not correspond to what the dental professional intends.

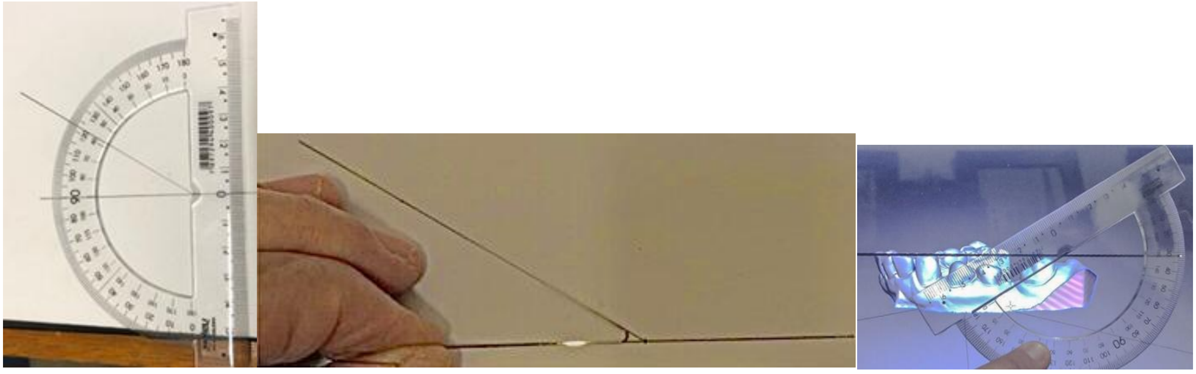
This study tested different lengths of the MTS nickel-titanium segment to evaluate whether the amount of wire used interferes with the moment and force generated in the region of the molar to be uprighted and in the anterior anchorage region. Specifically, activation of 30° in the posterior segment (β) and 0° in the anterior segment (α) was examined, with the horizontal connection of the nickel-titanium wire to the steel component fixed at distances of 0 mm (G0), 1 mm (G1), 2 mm (G2), and 3 mm (G3) away from the curvature of the nickel-titanium wire that fits into the molar auxiliary tube.

2 MATERIALS AND METHODS

An orthodontic mold of a patient with loss of the lower-left first molar was selected. The inclination of the lower-left second molar was measured using a template made with a protactor[7] in relation to the occlusal plane (Figure 1A–C).

Figure 1

Protractor-based template and angular verification of the mandibular second molar

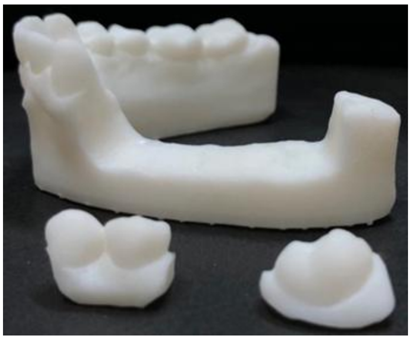


The standardization of the model involved (1A) the customized protractor template, (1B) the physical check of the 30° mesial inclination on the laboratory bench, and (1C) the digital confirmation of the molar position relative to the occlusal plane using Meshmixer software.

The mold was digitized with a desktop scanner (3Shape, Copenhagen, Denmark) and processed with Meshmixer software (Autodesk, Inc., San Rafael, CA, USA). The dental crowns of the first and second premolars and the second molar were cut out to be printed separately from the dental arch using a 3D printer (Form2; Formlabs, Somerville, MA, USA) for future fixation in the orthodontic force tester (OFT)[8] (Advanced Research and Technology Institute, Inc., Indianapolis, IN, USA; Patent US 6,120,287, 2000; Figure 2A, B).

Figure 2

Anatomical dental crowns printed via 3D technology



High-resolution 3D printing of the segmented dental crowns (first premolar, second premolar, and second molar), designed to be attached independently to the load cells of the Orthodontic Force Tester (OFT) for precise force recording.

In a second complete lower mold, the teeth on the left side were printed with heavy silicone (Zetalabor; Zhermack, Badia Polesine, Italy) to serve as a guide (Figure 2). The separately printed teeth were fixed to the base of the mold with wax (ASFER; Indústria Química Ltda., São Caetano do Sul, Brazil) using the silicone guide, which was removed after fixing was complete (Figure 3 A–D).

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Figure 3

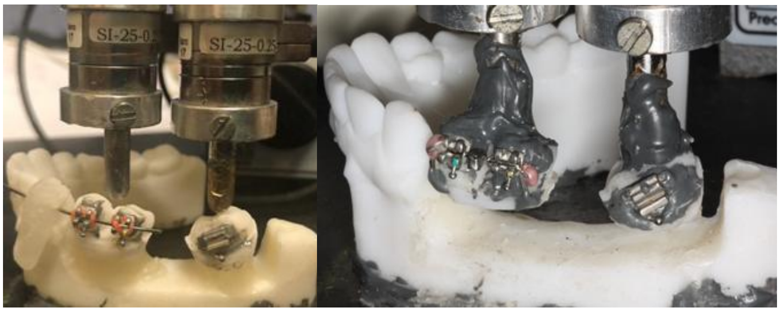
Sequential steps for experimental model assembly and teeth fixation

The preparation process consists of (A) the complete printed base, (B) the heavy silicone positioning guide, (C) the stabilization of the crowns using sticky wax, and (D) the final setup after guide removal, ensuring accurate inter-bracket relationships.

The mold with the individually printed teeth was then fixed to the base of the OFT[8] with epoxy glue (JB Weld; Sulphur Springs, TX, USA). Roth Sprint brackets (0.022"; Forestadent, Pforzheim, Germany) were attached to the lower left premolars with the same epoxy glue, and a double Roth tube (0.022") was attached to the lower left second molar. An SS wire (0.019" × 0.022"; Ormco; Glendora, CA, USA) was placed in the anterior segment, and a cross tube (0.022"; Forestadent, Pforzheim, Germany) was inserted between the premolars. The wire was tied to the bracket with elastic ligatures (GAC, Bohemia, NY, USA). Triad gel (Dentsply Sirona, Long Island City, NY, USA) was placed on the tips of the steel wire of the tip-back spring to protect against labial injury and to prevent movement out of the cross tube. OFT load cells were fixed between the lower left premolars, identified as T1, and the lower left molar, identified as T2 (Multi-Axis Force/Torque Nano17; ATI Industrial Automation, Apex, NC, USA). Each had a measured amplitude of 0-2,000 g (0.0–19,613.3 N) for force and between 0–10,000 g·mm (0.0-98,006.5 N·mm) for moments. After attaching the load cells, the wax was removed to allow movement of the teeth attached to the ends of the load cells (Figure 4 A, B).

Figure 4

Configuration of the multi-axis load cells on the Orthodontic Force Tester (OFT)



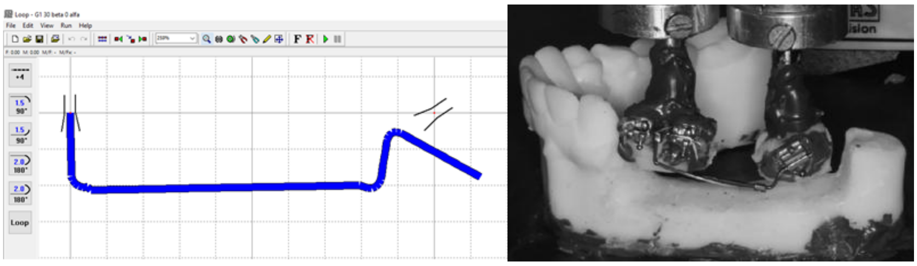
Detailed view of the Nano17 sensors: (A) strategic positioning of the T1 sensor between the premolars and T2 on the molar; (B) final fixation with epoxy glue and removal of the wax to allow unrestricted 3D measurement of forces and moments.

The OFT sensors were adjusted to transfer the origin of the 3D measurements to the cross tube between the lower left premolars and the double tube in the lower left molar; the x-axis was perpendicular, the y-axis parallel, and the z-axis vertical to the occlusal plane.

Each setup had 30° activation in the posterior segment (β), divided into four groups (G0, G1, G2, G3), in which the horizontal connection joining the nickel-titanium to the steel wire was fixed at 0, 1, 2, and 3 mm, respectively, away from the curvature of the arm that fits into the molar auxiliary tube. Each group consisted of five Sander springs, 0.017" × 0.022" in the steel segment and 0.018" × 0.025" in the nickel-titanium segment. (Forestadent, Pforzheim, Germany). The MTS was designed using Loop software (dHAL Software, Athens, Greece; Figure 5 A, B).

Figure 5

Digital planning interface and physical force measurement

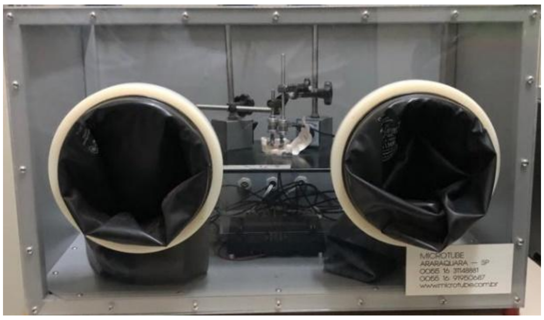


(A) The MTS design template within the Loop software environment for standardized geometry; (B) Clinical simulation showing the Memory Titanol Spring (MTS) activated and connected to the transducer system.

Before each measurement, the OFT software and the load cells were reset to zero. The whole system was placed in a temperature-controlled acrylic box at 37ºC (Figure 6).[9]

Figure 6

Thermal control chamber for intraoral environment simulation



The testing apparatus was housed in an acrylic glove box equipped with a heating system maintained at a constant temperature of 37ºC, essential for evaluating the superelastic properties of the nickel-titanium alloy under clinical-like conditions.

Forces were measured twice for each sample. The force and moment mean in the z-axis and y-axis (Fz and Ty) were tabulated in a spreadsheet compatible with Excel 2010 (Microsoft Office; Microsoft, Redmond, WA, USA). The data was analyzed using SPSS software (version 20.0; IBM, Armonk, NY, USA). Reproducibility between the Fz and Ty measurements in each sample was assessed using the interclass correlation coefficient (ICC) and its 95% confidence interval (CI), considering absolute precision and the two-factor mixed variance analysis cast for single measurements.[10] The value between the measurements was determined,[11] showing high precision (Fz: ICC = 0.992 [95% CI = 0.983-0.996]; Ty = 0.990 [95% CI = 0.979-0.995]). Subsequent analyses used the simple arithmetic mean between the two measurements for each sample.

Fz and Ty were analyzed descriptively for each tooth in the group. The normality of the distribution was assessed using the Shapiro-Wilk test. Homoscedasticity was assessed using Levene's F-test. When homoscedasticity was accepted, Fz and Ty were compared between the groups using a one-way analysis of variance (ANOVA), followed by Tukey's post-hoc test. When homoscedasticity was rejected, they were compared using ANOVA with Welch's correction followed by the Games-Howell post-hoc test.

3 RESULTS

Table 1

Descriptive statistics for Fz (N) - vertical force and descriptive statistics for Ty (N-mm) - moment in the sagittal plane. according to tooth and group

	Fz				Ty			
Group	Mean	SD	Min	Max	Mean	SD	Min	Max

Molar								
G0	-0.54	0.04	-0.59	-0.51	17.62	0.29	17.26	18.01
G1	-0.68	0.04	-0.73	-0.62	16.47	0.43	15.89	17.02
G2	-0.66	0.03	-0.69	-0.61	16.58	0.67	15.70	17.58
G3	-0.66	0.07	-0.76	-0.56	14.76	0.55	14.34	15.67
Premolar								
G0	0.56	0.04	0.52	0.63	1.49	0.15	1.31	1.65
G1	0.61	0.03	0.58	0.65	2.63	0.20	2.49	2.96
G2	0.56	0.04	0.52	0.60	2.44	0.15	2.26	2.62
G3	0.67	0.09	0.56	0.78	2.42	0.23	2.12	2.74

Table 1 shows the mean, standard deviation, maximum, and minimum values for molars and premolars. The molars showed extrusion of -0.54 N for G0, -0.68 N for G1, -0.66 N for G2, and -0.66 N for G3. On the other hand, in the anterior region of the mandibular premolars, the forces were predominantly intrusive, with a variation of 0.56 N for G0, 0.61 N for G1, 0.56 N for G2, and 0.67 N for G3. With regard to molar uprighting moments, Ty, the groups showed uprighting with a distal moment and mean of 17.62 N·mm for G0, 16.47 N·mm for G1, 16.58 N·mm for G2, and 14.76 N·mm for G3. With regard to the uprighting moments, Ty, of the premolars, groups G0, G1, G2, and G3 showed uprighting with a distal moment and mean of 1.49 N·mm, 2.63 N·mm, 2.44 N·mm, and 2.42 N·mm, respectively.

Table 2

Comparison of the mean forces and moments between the three groups

Force	SQ	QM	F	p-value	η^2_p
Molar					

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Fz	Between groups	0.062	0.021	8.615	0.001	0.618
	Within groups	0.038	0.002			
	Total	0.100				
Ty	Between groups	21.080	7.027	27.327	<0.001	0.837
	Within groups	4.114	0.257			
	Total	25.194				
Premolar						
Fz	Between groups	0.037	0.012	3.180*	0.081	0.428
	Within groups	0.050	0.003			
	Total	0.087				
Ty	Between groups	3.940	1.313	37.525	<0.001	0.876
	Within groups	0.560	0.035			
	Total	4.500				

*With Welch's correction

Table 2 shows the average difference and statistical measures between the three groups examined. A difference can be observed for each tooth in at least one pair of groups.

Table 3

Mean and standard deviation of the Fz (N) and Ty (N-mm) variables according to the tooth and the group

Group	Fz	Ty
Molar		
G0	-0.54 (0.04)^{B}	17.62 (0.29)^{C}
G1	-0.68 (0.04)^{A}	16.47 (0.43)^{B}
G2	-0.66 (0.03)^{A}	16.58 (0.67)^{B}
G3	-0.66 (0.07)^{A}	14.76 (0.55)^{A}
Premolar		
G0	0.56 (0.04)^{A}	1.49 (0.15)^{A}
G1	0.61 (0.03)^{A}	2.63 (0.20)^{B}
G2	0.56 (0.04)^{A}	2.44 (0.15)^{B}
G3	0.67 (0.09)^{A}	2.42 (0.23)^{B}

^{ABC} Comparison between groups for same tooth and force; different letters indicate statistical difference α=0.05

Table 3 compares the forces and moments between the three groups examined. All the groups showed different forces and moments.

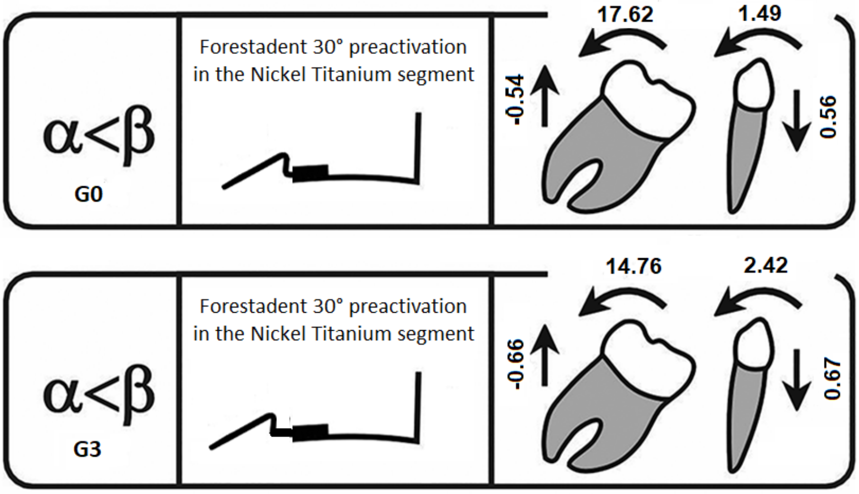
4 DISCUSSION

As a general result, this work validates that the spring distance used is critical for generating a desirable effect of biological force and moment levels.[12] In order to compare the results of this study with the theoretical model proposed by Wichelhaus and Sander, the focus was on vertical forces and moments. It was shown that the spring generated extrusive force in the posterior region and intrusive force in the anterior region. In their work, Wichelhaus and Sander[5] propose that the molar, where the activation is α<β, should undergo uprighting accompanied by extrusion, while the premolars undergo mesial moment and intrusion. The direction of the forces was therefore consistent with the original theoretical proposal. However, we observed differences in the moments of the premolars in the opposite direction. This can be explained by the greater flexibility of the nickel-titanium alloy in the posterior region.

Sander and Wichelhaus's proposal[4] was to join two different alloys to avoid side effects. A steel rod in the anchorage unit stabilizes it because it is an alloy with little flexibility and a lot of rigidity. This allows the nickel-titanium alloy to work with its flexibility, causing a moment in the molar. However, our results show that the steel wire does not behave as desired by Sander and Wichelhaus. In general terms, this was probably due to the combination of a stiffer wire with a more flexible one, which resulted in the generation of a class III geometry.[13] The theoretical idea of a rigid wire in the area of stability and a flexible wire in the area of greatest movement did not prove true in this work.[6] (Figure 7).

Figure 7

Force system diagrams for molar uprighting activations G0 and G3



Vector illustration of the resulting mechanical systems: the arrows indicate the direction of vertical forces (Fz) and distal moments (Ty), demonstrating the consistency between experimental results and the theoretical Burstone Class III geometry [8888]. **Source:** Adapted from Wichelhaus and Sander (1995).

Pinheiro[14] showed using photo elasticity that the 0º activations in the anterior segment proposed by Sander and Wichelhaus created areas of tension on the molar side when compared to a simple cantilever, with all the devices having a distal vertical moment. This study did not assess vertical forces. On the other hand, in the reactive anterior region of the premolars, the MTS with 0º activation in the anterior segment behaved similarly to the simple cantilever. This data is inconsistent with the present study, which may be explained by the fact that Pinheiro's study was qualitative, while the present study was quantitative and used a more sensitive system for measuring forces and moments.

The ideal moment intensity for vertical molars is 10–15 N·mm.[15] With this in mind, all the variations tested in this study behaved acceptably in relation to the molar. There does not seem to be much interference from the distance factor in this regard. Vertical force was low in both the anterior and posterior segments and is very likely to be neutralized by occlusal forces, especially in normal and hypodivergent patients,[16] considering that the average occlusal load of the molars was 30.54 Kgf on the left and 23.53 Kgf on the right.[17]

In a laboratory study, Shibasaki and Martins[18] compared different tube heights in inclined molars, using continuous nickel-titanium wires (0.016" × 0.022") and an OFT for measurements. They concluded that a force system always generates posterior extrusive and anterior intrusive forces. The present study is compatible with these data, including the intensity of the forces and moments and the geometric pattern of the Burstone Class III system. The vertical forces varied between -0.75 and -1.31 N, and the moments between 11.84 and 13.98 N·mm in the molar. Therefore, the choice between continuous wires and MTS is more related to personal preference than to mechanical factors in the force systems. Shibasaki and Martins[18] also suggest using a more occlusally positioned tube on the molar, which, from a clinical point of view, may not be viable due to contact with the antagonist. If the orthodontist still chooses to raise the bite, extrusive forces are more easily manifested due to the absence of antagonistic occlusal forces. This study is limited by having tested only one preactivation configuration of the MTS. It is important to recognize that any alterations in the preactivation, even if similar to the one previously tested, [19] could result in significant differences in the force system, as well as the magnitude of the forces and moments generated.

5 CONCLUSIONS

1- The change in the length of the nickel-titanium segment in Memory Titanol® Spring showed a statistical difference between the four groups tested, mainly in group G0.

However, these differences may not be clinically significant as all values fell within the moment intensity of 10–15 N·mm required to upright molars.

2- All the pre-activations tested (G0, G1, G2, and G3) showed extrusive forces in the molars and intrusive forces in the premolar region, but at a low level.

3- The G0 group's pre-activations were the most favorable in terms of intensity.

4- On the anchoring side, in the anterior region, all four groups showed moments in the distal direction, but at a low intensity and probably sub-optimal level.

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