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Original Article

Development of an orthodontic simulator for measurement of orthodontic forces

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In this research we developed an orthodontic simulator for analysis of orthodontic forces distribution in the case of the continuous arch technique. In order to take into account vertical force, besides horizontal force and occlusogingival moment on instrumented artificial tooth, tooth root was designed as a ring load cell. Fixing each artificial tooth onto combined mechanical stages enabled variation of tooth anteroposterior position and inclination related to occlusal plane. Calibration of forces and moment of each instrumented artificial tooth showed linearity of outputs and provided the generalized inverse matrix for evaluation of forces and moments from measured strain data. A simulation to retract the anterior teeth was accomplished, and distribution of forces and moment acting at the bracket of each tooth were determined. The average accuracy was 82% and 97% in the horizontal and vertical direction, respectively, by comparing the applied forces and the evaluated ones.

Key words: Orthodontics, Simulation, Orthodontic tooth movement, Orthodontic forces, Mechanics in orthodontics

Introduction

Orthodontic treatment is viewed as a long-time and stressing dental treatment, not only for the patient but for the orthodontist as well. It demands a detailed mechanical planning for treating the malocclusion before the start of treatment, and even so, more often than expected, after months waiting for a tooth movement to a certain direction, the orthodontist faces that the tooth has moved into a wrong position. Thus, prediction in orthodontics becomes fundamental for an efficient and successful treatment, since unexpected movements take additional time, and sometimes generate irreversible problems.

Despite its importance, not much research on the prediction of movement of teeth in orthodontics has been reported, especially in the case of the continuous arch technique. Simulation can be a powerful approach, and we developed an orthodontic simulator for measurement of orthodontic forces in the case of the continuous arch technique. A brass cylinder sensor[2] adopted as tooth root enabled measurements of horizontal force and moment of force, but not vertical force. Since vertical force, or force to intrude or extrude a tooth, is also a component that can not be neglected in orthodontics, the present orthodontic simulator was projected to provide the vertical force measurement as well by designing tooth root as a ring load cell. By including the vertical component, tooth inclination related to occlusal plane can also be taken into account as another experimental variable, which has not been considered up to now[2,3].

Materials and Methods

Four brass rings, with outer diameter, inner diameter, and width of 20 mm, 18 mm, and 5 mm, were fabricated as tooth root load cells. Computer simulation using the finite element method[1] (ABAQUS, H, K & S Inc.) provided the optimum points of greater strains for adhering ten strain-gauges (Kyowa KFG-02-120-C1-

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23) to each ring, five internally, and five externally. The finite element method model of the ring is shown in Figure 1.

Four resin anterior superior teeth were mounted on the ring sensors, and each tooth-ring set was fixed onto a goniometer G and x-axis stage S (Chuo Seiki LS-347-C1 and TS-311), which enable variation of tooth inclination related to occlusal plane θ and anteroposterior position δ, as Figure 2 shows. The position of the ten strain-gauges is represented by the thick black lines inside and outside the ring. Tooth rotates about the goniometer's center of rotation h, assumed coincident with tooth root's center of resistance C_{Res}. The center of resistance of a tooth root[4] is determined at 0.4 H, where H is the amount of tooth covered with bone, which was taken based on the Japanese women's average dental anatomy[5].

Calibration of each model was accomplished by applying known values of horizontal force, vertical force, and occlusogingival moment to each tooth separately to obtain the corresponding values of strains for construction of the generalized inverse matrix. This approach enables evaluation of forces and moment from measured strain data.

The four instrumented anterior teeth models and the second premolars and first molars of each side were mounted on a 5-mm thickness steel plate to constitute an “upper maxilla”, as Figure 3 shows. The second premolars and first molars were adjusted adequately in height with the anterior teeth by fixing them on a brass support at each side. The curvature of the dental arch followed a preformed nickel-titanium arch wire (Tomy Sentalloy 0.016 × 0.022 inch). The steel plate had enough rigidity not to interfere in the measurement outputs.

All teeth were connected up by inserting the preformed nickel-titanium arch wire cited above through Roth type brackets (Tomy 0.018 inch slot), bonded to the crown of each anterior tooth, and triple tube brackets (Tomy 0.051 inch), bonded to the first molars. The brackets were bonded to the teeth with the anterior teeth inclined at 60 degrees with the occlusal plane, as to induce as minimum stress as possible on the wire.

A simulation was conducted to retract the anterior teeth aligned and inclined at 60 degrees with the occlusal plane. Weights of 50, 100, 150, and 200 g were loaded at the end of each side of the arch wire, as Figure 4 shows, to represent retracting forces applied on the wire as if the first molars were used as anchor

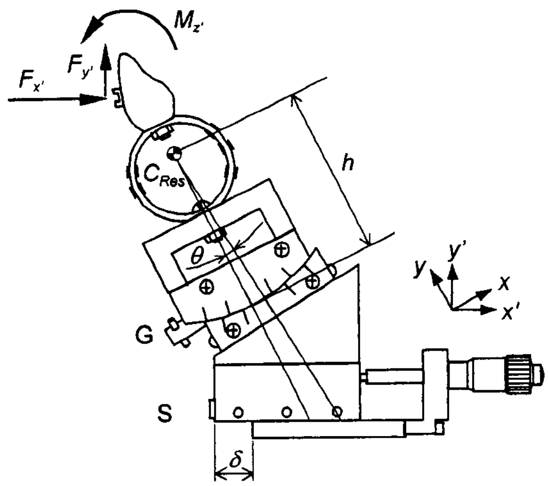

Figure 2. Orthodontic simulator with tooth root designed as a ring sensor.

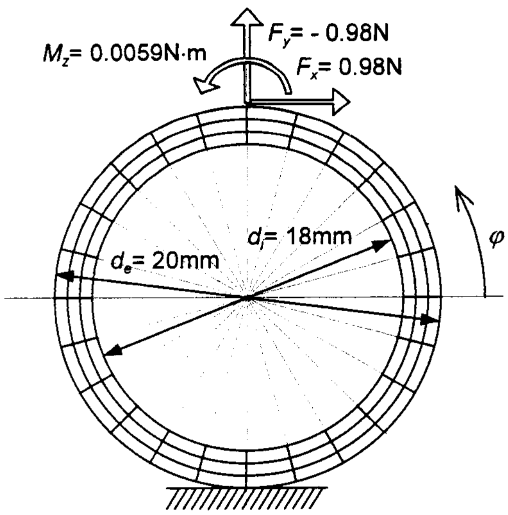

Figure 1. Ring model for FEM analysis.

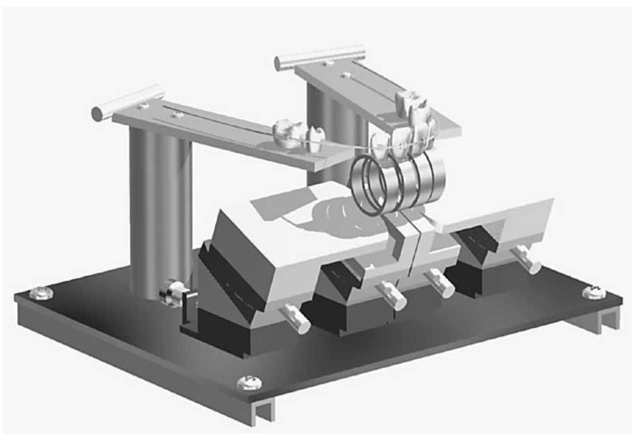

Figure 3. Simulator assemblage.

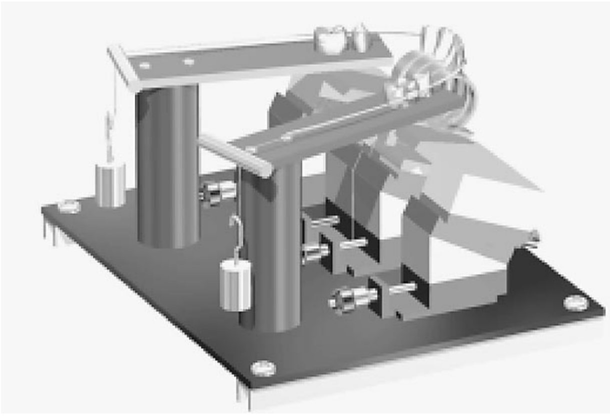

Figure 4. Simulation procedure.

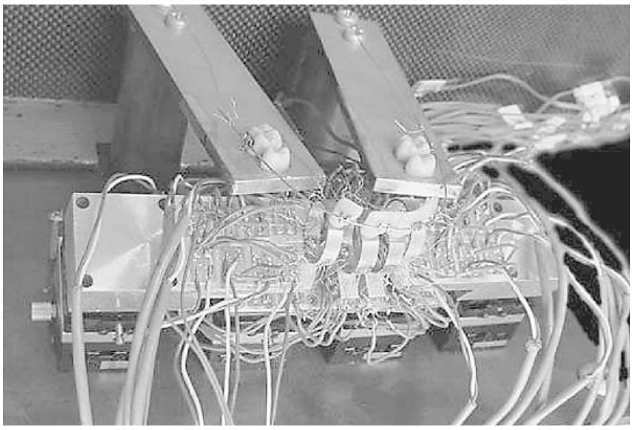

Figure 5. "Upper maxilla" orthodontic simulator.

teeth, which did not move. Data from forty strain-gauges were acquired simultaneously through a switching box (Tokyo Sokki Kenkyusho ASW-50C) and a digital strain meter (Tokyo Sokki Kenkyusho TDS-302) to a personal computer (Epson PC-486GR). The actual simulator is seen in Figure 5.

Data Processing

Horizontal force F_x , vertical force F_y , and occlusogingival moment M_z acting at the bracket of each tooth were evaluated from measured strain data.

Strains induced on the strain-gauges by applying known loads of F_x , F_y , and M_z to the tooth models are given by

$$\begin{aligned} \varepsilon_1 &= c_{1x}F_x + c_{1y}F_y + c_{1z}M_z \\ \varepsilon_2 &= c_{2x}F_x + c_{2y}F_y + c_{2z}M_z \\ &\vdots \\ \varepsilon_n &= c_{nx}F_x + c_{ny}F_y + c_{nz}M_z \end{aligned} \qquad (n = 10)$$

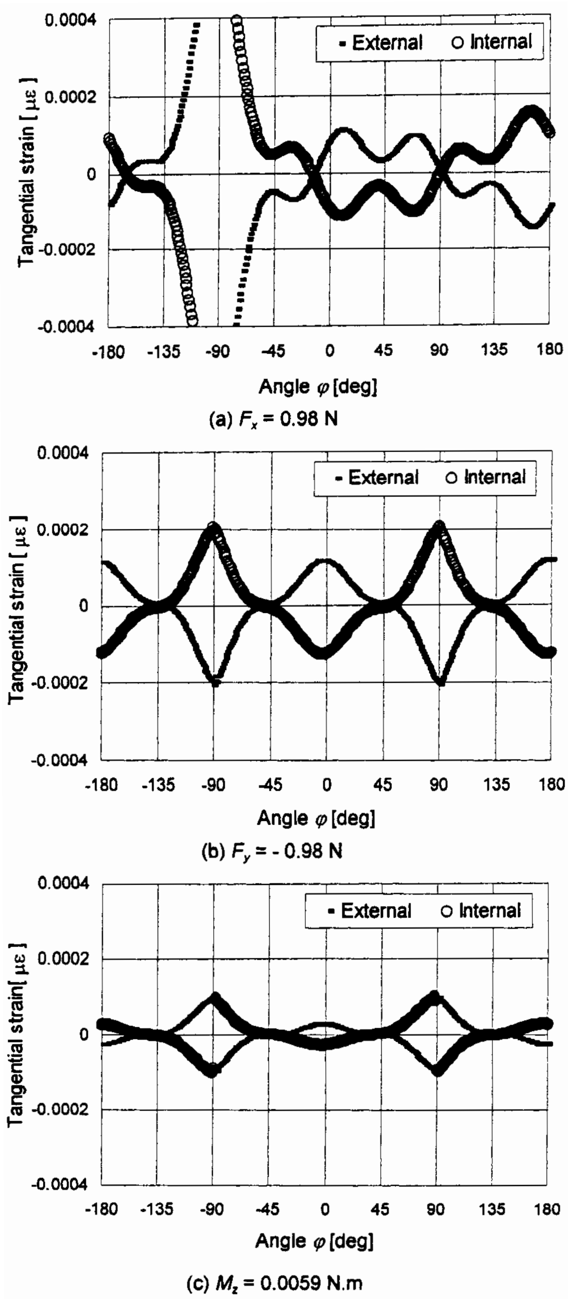

Figure 6. Strain distribution on the ring by the finite element method.

Coefficients c_{ij} (i = 1,2, ... n; $j = x,y,z$) are determined from calibration, where i denotes strain-gauge and j, the respective load.

In matrix notation, the above equations can be represented as $\varepsilon = \boldsymbol{CF}$, in which $\varepsilon = (\varepsilon_1, \varepsilon_2, \ldots, \varepsilon_n)$ and $\boldsymbol{F} = (F_x , F_y , M_z)$. By inverting matrix $\boldsymbol{C}$ and multiplying it by the strains measured from experiment, the forces act-

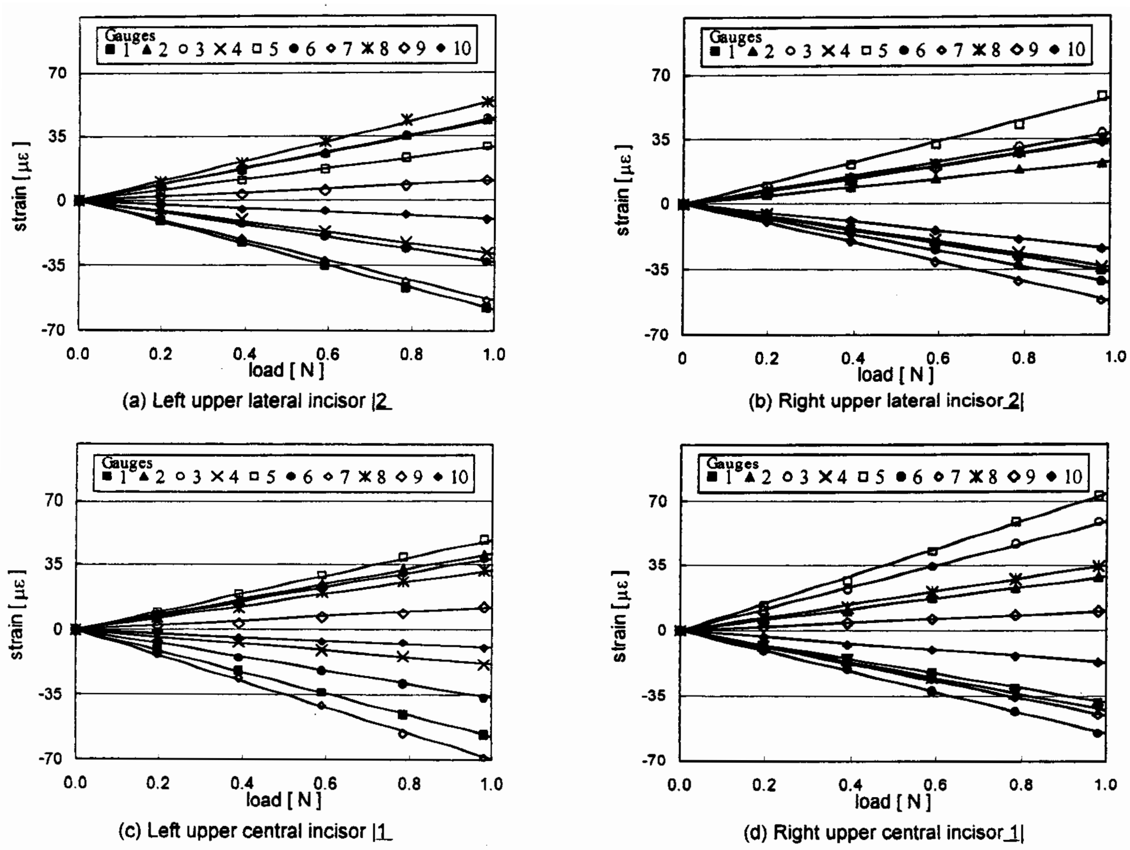

Figure 7. Individual calibration of horizontal force.

ing on each tooth are obtained as $\boldsymbol{F} = \boldsymbol{C}^{-1}\,\varepsilon$. Matrix $\boldsymbol{C}^{-1}$ was called as the generalized inverse matrix and was obtained through singular value decomposition method with the use of Matlab, Mathworks Inc.

Results

Normal and shear strains obtained from the finite element method for horizontal force of 0.98N, vertical force of -0.98N and moment of 0.0059N · m applied on the ring were transformed into tangential strains. The tangential strains distribution graphs are shown in Figure 6. The points of greater strains that could be used for adhering the strain-gauges on the ring were defined at 0, 15, 175, 180, and -30 degrees internally and externally.

Figure 7 shows experimental data for calibration of the horizontal force F_x. Strain data were measured for loads of 0.20, 0.39, 0.59, 0.78 and 0.98N (weights of 20, 40, 60, 80 and 100g), and coefficients c_{ix} (i = 1,2, ... n) were obtained through the least square method. Vertical force F_y and occlusogingival moment M_z were calibrated in the same way.

Table 1 shows individual calibration accuracy for each instrumented anterior tooth model by comparing experimentally given values of F_x = 0.98N, F_y = –0.98N and $M_z = 1000 \times 10^{-5}$N · m with values obtained through generalized inverse matrix from measured strain data.

Figure 8 shows strain data obtained from simulation experiments for total loads of 0.98, 1.96, 2.94, and 3.92N induced on the wire, which correspond to loads of 0.49, 0.98, 1.47, and 1.96N (weights of 50, 100, 150, 200g) induced on each side of the arch wire.

Table 2 shows values of horizontal force F_x , vertical force F_y , and moment M_z in the tooth's coordinate system, evaluated through generalized inverse matrix, and values of horizontal force $F_{x'}$, vertical force $F_{y'}$, and moment $M_{z'}$ in the simulator's coordinate system, obtained through coordinate system transformation, for total retracting force R of 0.98, 1.96, 2.94, and 3.92N induced on the wire.

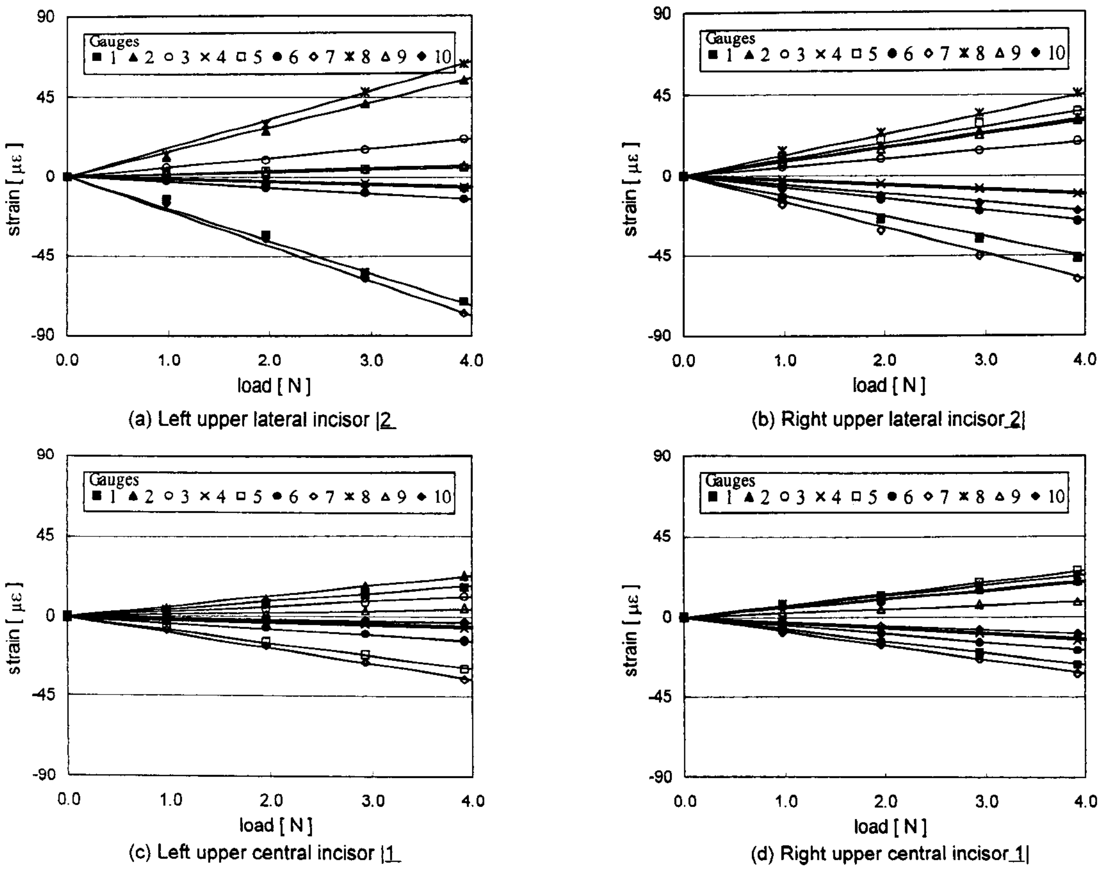

Figure 8. Strain data from simulation.

Discussion

The excellent linearity of all outputs for horizontal force in the individual calibration (Figure 7) indicates that the measurements from the strain-gauges were reliable, since strain is proportional to force. The same linearity was also confirmed for vertical force and occlusogingival moment.

Validity of the data processing method was verified. In Table 1, by comparing theoretical values of F_x, F_y, and M_z with values obtained from the generalized inverse matrix, it might be considered that the data processing was performed successfully. The accuracy was near 100% in all cases, with horizontal force for the left central incisor being the less accurate one, but still with accuracy of 99%.

In Table 2, values of horizontal force F_x, vertical force F_y, and occlusogingival moment M_z in the tooth's coordinate system *xyz* correspond to results evaluated through the generalized inverse matrix of each tooth. Since calibration of the teeth was accomplished with the ring sensor upright, and the simulation, with the teeth inclined at 60 degrees, these forces are transformed into forces $F_{x'}$, $F_{y'}$, and $M_{z'}$ in the simulator's coordinate system *x'y'z'* in Table 2 through coordinate system transformation.

For a total retracting force *R* of 0.98N in Table 2, $F_{x'}$ and $F_{y'}$ yields to resultants $F_{x'} = 77.79 \times 10^{-2}$N and $F_{y'} = -2.09 \times 10^{-2}$N, which correspond to 79% and 98% accuracy in the horizontal and vertical direction, since the total force applied was a 0.98-N only in the horizontal direction, and therefore, it was expected $F_{x'}$ = 0.98N and $F_{y'}$ = 0 (zero). For retracting forces *R* of 1.96N, 2.94N, and 3.92N, the same order of accuracy was obtained: 82%, 84%, and 83% in the horizontal direction, respectively, and 98%, 96%, and 96% in the vertical direction, respectively. All values give a total average accuracy of 82% and 97% in the horizontal and vertical direction. Naturally, in the horizontal direction, considerable amount of loss is associated to friction between the wire and the molars' tube brackets, since the forces applied on the wire were weights at the end of each side of the wire. Taking into account such phenomenon and the final results, we may consider

Table 1. Individual calibration accuracy

Tooth		Force applied on tooth: F_x = 0.98 [N] Theory	F_x = 0.98 [N] Evaluated	F_y = - 0.98 [N] Theory	F_y = - 0.98 [N] Evaluated	M_z = 1000 [10^{-5} N·m] Theory	M_z = 1000 [10^{-5} N·m] Evaluated
Left lateral incisor |2	F_x [10^{-2} N]	98.0665	98.0665	0	0.0021	0	0.0431
	F_y [10^{-2} N]	0	0	-98.0665	-98.0651	0	0.0068
	M_z [10^{-5} N·m]	0	0.0002	0	-0.0540	1000	1001.304
Left central incisor |1	F_x [10^{-2} N]	98.0665	97.8806	0	0	0	0
	F_y [10^{-2} N]	0	-0.2619	-98.0665	-98.0665	0	0
	M_z [10^{-5} N·m]	0	8.6821	0	-0.0008	1000	1000.277
Right central incisor 1|	F_x [10^{-2} N]	98.0665	98.0665	0	0	0	0
	F_y [10^{-2} N]	0	0	-98.0665	-98.0665	0	0
	M_z [10^{-5} N·m]	0	0	0	0	1000	1000.277
Right lateral incisor 2|	F_x [10^{-2} N]	98.0665	98.0664	0	0	0	0
	F_y [10^{-2} N]	0	0	-98.0665	-98.0664	0	0
	M_z [10^{-5} N·m]	0	0.0002	0	0.0001	1000	1000

Table 2. Individual forces acting on teeth in tooth's and simulator's coordinate system.

		Tooth's coordinate system			Simulator's coordinate system		
R	Tooth	F_x [10^{-2} N]	F_y [10^{-2} N]	M_z [10^{-5} N·m]	$F_{x'}$ [10^{-2} N]	$F_{y'}$ [10^{-2} N]	$M_{z'}$ [10^{-5} N·m]
0.98 N	Left lateral incisor |2	20.27	- 8.21	- 46.70	21.66	- 3.02	- 46.71
	Left central incisor |1	6.77	- 5.71	-132.00	8.72	1.56	-131.99
	Right central incisor 1|	16.57	- 7.41	- 91.00	18.06	- 1.86	- 90.99
	Right lateral incisor 2|	24.83	-15.71	- 7.03	29.37	1.19	- 7.03
1.96 N	Left lateral incisor |2	47.28	-21.55	-117.53	51.72	- 4.98	-117.53
	Left central incisor |1	15.46	-11.95	-308.30	19.36	2.61	-308.30
	Right central incisor 1|	30.83	-14.08	-182.40	33.74	- 3.22	-182.40
	Right lateral incisor 2|	47.27	-28.35	- 26.39	55.11	0.92	- 26.40
2.94 N	Left lateral incisor |2	76.23	-36.52	-184.39	84.28	-6.49	-184.39
	Left central incisor |1	26.55	-16.97	-536.23	31.48	1.42	-536.23
	Right central incisor 1|	49.06	-19.80	-333.50	52.38	-7.38	-333.50
	Right lateral incisor 2|	68.84	-39.96	- 41.94	79.60	0.19	- 41.94
3.92 N	Left lateral incisor |2	101.79	-46.45	-247.93	111.38	-10.67	-247.93
	Left central incisor |1	35.93	-23.16	-723.62	42.09	2.09	-723.62
	Right central incisor 1|	63.84	-25.86	-413.72	68.22	- 9.53	-413.72
	Right lateral incisor 2|	89.84	-53.03	- 56.70	104.32	1.00	-723.62

that our simulator presented satisfactory accuracy.

With regard to magnitude of force acting on each tooth, the results in Table 2 indicate greater horizontal force $F_{x'}$ on the lateral incisors than on the central incisors, but the opposite for occlusogingival moment $M_{z'}$, that is, moment was greater for the central incisors than for the lateral incisors. Vertical force $F_{y'}$ was insignificant on all anterior teeth as expected. One would have expected distribution of forces of the same order for symmetrical teeth, since the force applied on the wire was symmetric. However, though the wire was inserted in the brackets as to induce as minimum stress as possible on it, in reality differences of contact between the brackets and the wire existed, producing points of greater or lesser friction, and generating a non-uniform distribution of forces. Thus, this curious distribution of horizontal force and moment on the teeth was not trivial and could not be predicted by only inserting the wire in the brackets and retract the teeth. This reinforces the importance of prediction by simulation.

A possible line of research using the present simulator could be obtaining as much data as possible from simulation to develop, say, a software program in which behavior of teeth could be checked by inputting patients' data and desired forces.

There is much to develop to reach a real orthodontic treatment simulation. Nevertheless, we believe that the results obtained by our simulator contributed to enlighten the obscure field of distribution of forces in orthodontics. It is worthwhile a future research to get more clues that can make an orthodontic treatment as predictable and consistent as possible.

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