Original Article

Molar Distalization with a Modified Pendulum Appliance—In Vitro Analysis of the Force Systems and In Vivo Study in Children and Adolescents

Gero S. M. Kinzinger[a]; Heiner Wehrbein[b]; Peter R. Diedrich[c]

Abstract: The standard pendulum appliance was modified by integrating a distal screw into its base and by special preactivation of the pendulum springs. The suitability of this Pendulum K for the translatory distalization of maxillary molars was investigated in an in vitro analysis and in an in vivo study in children and adolescents. The in vitro measurement of the resulting force systems revealed that all forces and moments remained virtually constant over a three-mm simulated distalization increment. The transverse force, Fx, increased from two to 11 cN and the weakly intrusively acting force, Fy, from six to eight cN, but these increases were not statistically significant. The distalization force, Fz, initially 201 cN, was still 199 cN after a three-mm distalization increment. The mesially acting moment, My, rose from 1654 to 1834 cN mm, whereas the palatally acting moment, Mz, declined slightly from 229 to 164 cN mm. The slight, consistent distoinclinatory moment, Mx, initially 306 cN mm, was 310 cN mm after three mm. In parallel, the in vivo study with its collective of 66 patients confirmed that the Pendulum K allows a virtually translatory molar distalization with slight tippings of 4.75° to the palatal plane and 4.25° to the anterior basal plane. Palatal movements of the first molars were avoided. The proportion of molar distalization in the total movement was 73.53%. (*Angle Orthod* 2005;75:558–567.)

Key Words: Pendulum appliance; Molar distalization; Force-moment measurement

INTRODUCTION

Compliance-dependent appliances have been traditionally used for the distalization of upper molars. For over a decade, growing concerns about wearing time and esthetic impairment[1–3] have resulted in exclusively intraoral appliances, which are largely independent of patient compliance, being used with increasing frequency.

In recent years, clinical interest has focused in particular on the different pendulum appliances.[4–25] The aim of molar distalization should be maximum bodily tooth movement, on the one hand to minimize the risk of root resorptions and on the other to permit subsequent bodily retraction of the anterior dentition. The standard pendulum appliance introduced by Hilgers,[4] however, gives rise to the appliance-specific fundamental problem that once the activated pendulum springs have been inserted into the palatal sheaths of the molar bands, the molars are moved in an arc on pendulumlike radii. The potential consequences are palatal movements of the molars and tipping of the dental crowns. Our own modification, the Pendulum K, is aimed at preventing these side effects through the incorporation of a distal screw into the Nance button and the initial application of an uprighting and a toe-in bend in the region of the pendulum springs.

The aim of this study was to investigate whether the Pendulum K is suitable for the translatory distalization of upper molars by means of an *in vitro* analysis of the forces and moments acting orthodontically at the first molars. In addition, the clinical efficiency of our own modification was to be compared with that of other types of pendulum appliances in an *in vivo* study involving 66 children and adolescents.

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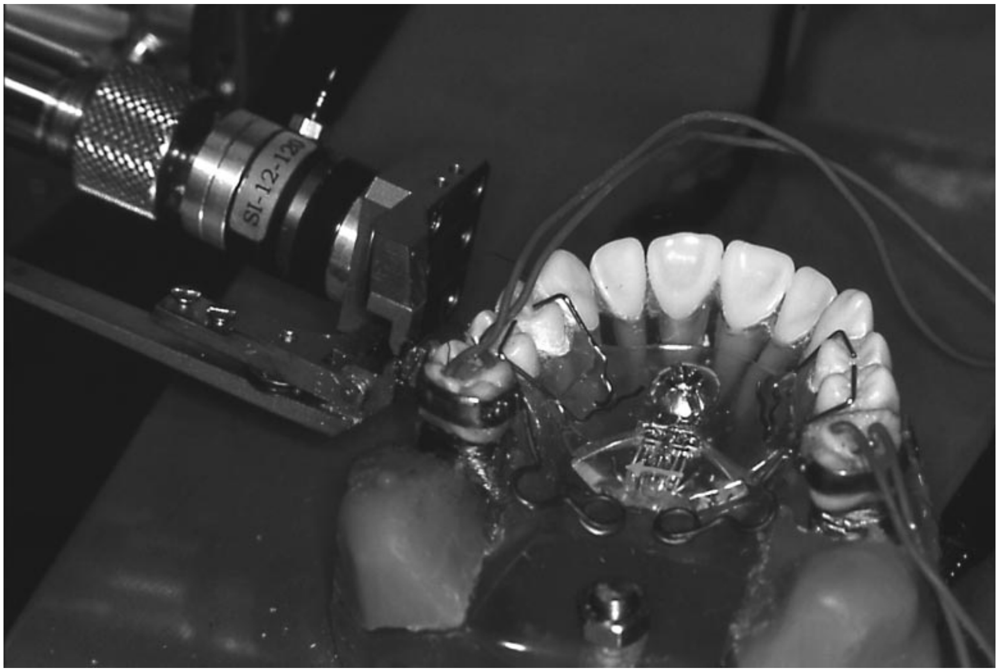

FIGURE 1. In vitro measurement: artificial jaw as anchorage unit and electrothermodynamic molars, rigidly fixed Pendulum K, coupled force-moment sensor.

MATERIALS AND METHODS

In vitro measurement

Test setup. The test setup comprised an artificial maxilla of pressurized polymer with 10 rigidly fixed teeth as anchorage unit, two electrothermodynamic molars,[26] electronic measuring unit for thermal control and regulation,[26] sensor unit with force-moment sensor, analog/digital converter, and data readout unit (Figure 1).[27–29]

The molars were fitted with prefabricated orthodontic metal bands, each of which had a special bracket (Dentaurum, Ispringen, Germany) lasered onto the buccal face. The three-dimensional sensor was connected with the lock section of the special bracket by means of a clamping device at the start of the measuring procedure and then maintained in this position relative to the molar by means of a retaining device. As the central element of the measuring apparatus, the measuring sensor registered six components (three forces and three moments) simultaneously in a measuring range of up to 10 N/100 N mm, with a resolution of 0.05 N/0.1 N mm. Three specimens of each Pendulum K were developed in the dental laboratory.

Measuring procedure, sign convention. The pendulum appliances were screwed rigidly to the artificial maxilla. The parameters measured were the force systems transmitted to the first molars by the pendulum springs after activation with a distalization force of 200 cN and after uprighting activation (30°) and provision of a toe-in bend (15°). The forces and moments were registered in all three dimensions at baseline and after distalization increments of one, two, and three mm. The distal screw incorporated in the Nance button of the Pendulum K was continuously adjusted (10 times per one mm simulated distalization increment). Each pendulum appliance was measured four times on each side, ie, the appliance type was measured 24 times overall.

The component tooth, band, and palatal sheath were regarded as rigid. The dentition of the artificial maxilla ended with the six-year molars, without any second and third molars. The first molars could thus be moved without interference from adjacent distal teeth under the influence of the preactivated pendulum springs. Reactive forces and moments on the anchorage unit were not measured.

The data from the measuring series were registered and stored in the data readout unit. To facilitate interpretation of the results and for biomechanical analysis, the system of coordinates and the convention governing signs were selected in accordance with the recommendations of Burstone and Koenig.[30] All mesially or buccally directed and extruding forces and all moments inducing mesially inward rotating and buccally rotating movements of the tooth crown and uprighting of the root are preceded by a positive sign. All contrary, distally or lingually directed and intrusive forces and moments inducing mesially outward rotating or palatally rotating crown movements are preceded by

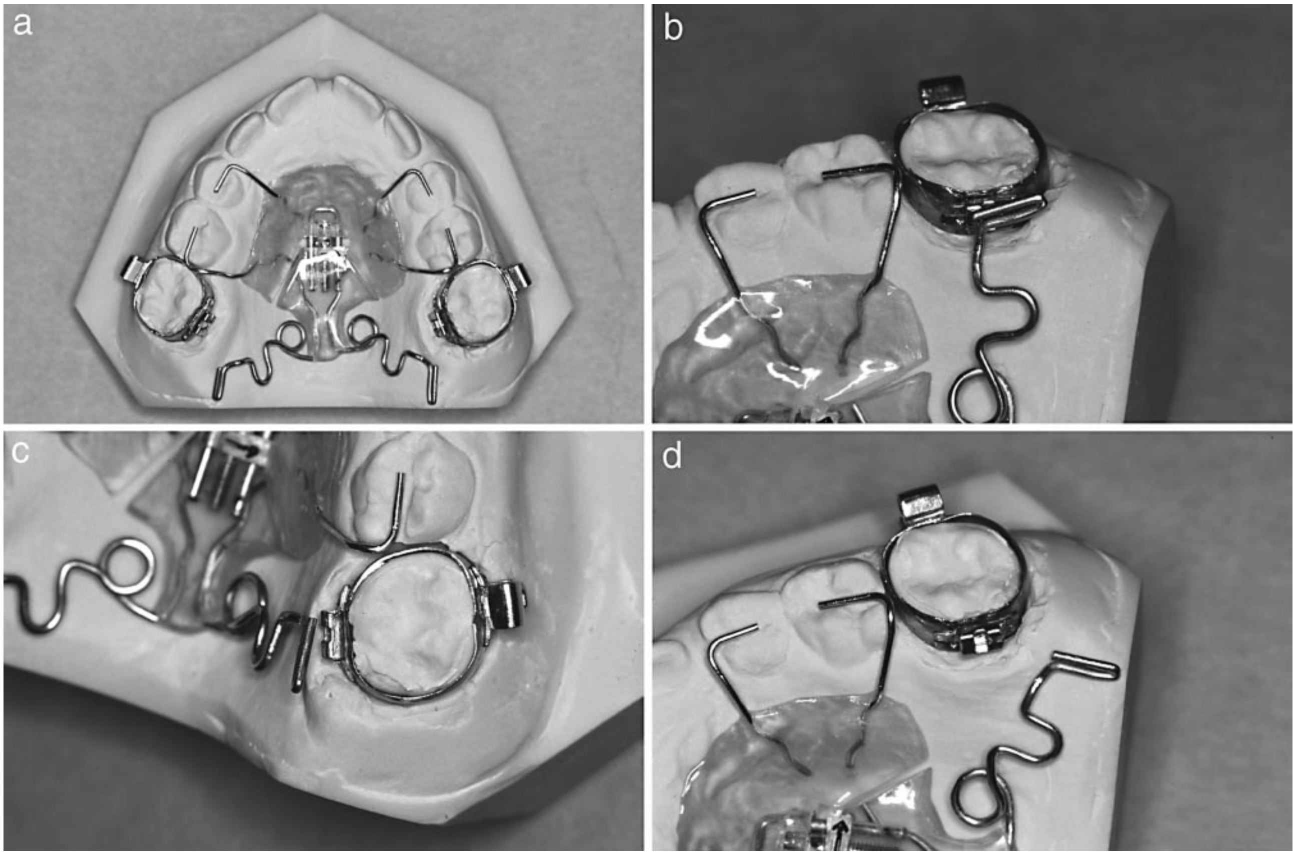

FIGURE 2. Pendulum K with distal screw (a) and integrated uprighting activation (b), toe-in bend (c), and distal activation (d) in the region of the pendulum springs for bilateral molar distalization in children and adolescents.

a negative sign. The x-axis shows tooth movements in the transverse, the y-axis in the vertical, and the z-axis in the sagittal plane.

In vivo study

Patients and appliance. A total of 66 children and adolescents (39 girls, 27 boys; mean age 11 years and eight months), presenting a dentoalveolar Class II malocclusion and a sagittal arch length discrepancy, had a modified pendulum appliance inserted in the maxilla for bilateral molar distalization. The mean treatment period was 22 weeks (Table 1). In 47 patients, the second molars were still unerupted, whereas the 12-year molars had already erupted in 19 cases.

The pendulum appliance used in this study (Pendulum K, Figure 2) had a distal screw that divided the Nance button into two parts, ie, an anterior part for anchorage purposes and a posterior part containing the active elements of the appliance, the pendulum springs. Before insertion, these pendulum springs were activated for distalization (targeted force 180–200 cN) and were given additional integrated uprighting activation (30°) and a toe-in bend (15°). During the routine appointments, the orthodontist intraorally reactivated the appliance by adjusting the distal screw without the pendulum springs having to be removed from the palatal molar sheaths. Ten adjustments of the distal screw yielded an additional force application of 50 cN.

Dental cast analysis. To check the molar movement in the horizontal plane, dental plaster casts were made at the beginning of treatment (T1) and after removal of the pendulum appliances (T2). Changes in the molar region were determined by measuring the corresponding casts with a digital caliper to record any increase or decrease in transverse dental arch width in the first and second molar region as well as the extent and type of rotation for each molar. The distance between the lowest point of the central fossa and the mesiobuccal (mb) and distobuccal (db) cusps of the first and second molars was registered bilaterally on the respective casts. In addition, the angles between a line running through the mb and db cusps and the midpalatal raphe were measured (Figure 3).

Cephalometric analysis. The lateral cephalograms taken at the beginning of treatment (T1) and on completion of distalization (T2) were analyzed to determine changes in the following parameters (Figure 4).

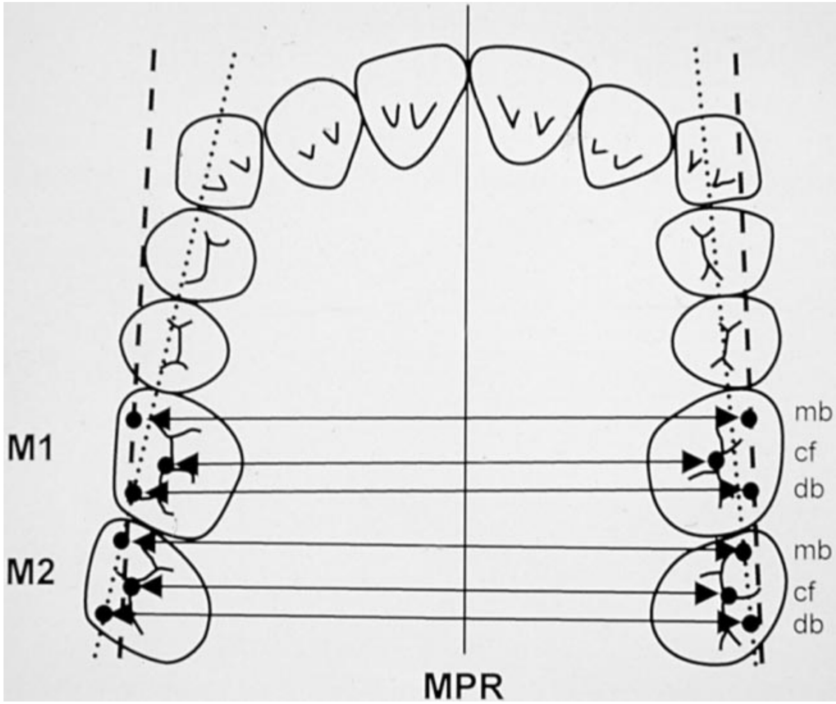

FIGURE 3. Cast analysis (changes in the horizontal plane): angular and linear measurements to determine changes in transversal dental arch width and in rotation in the region of the first (M1) and second molars (M2).

In the sagittal plane:

- The relative mesial movement of the incisors and thus the anchorage loss and the relative distal movement of the first and second molars to the pterygoid vertical were measured (U1-CEJ/PTV; U6-CEJ/PTV; U7-CEJ/PTV).
- The angles between the long axis of the individual teeth and the palatal plane or the anterior cranial base, respectively (U1/ANS-PNS, U1/SN; U6/ANS-PNS, U6/SN; U7/ANS-PNS, U7/SN), were used to determine the extent of labial tipping of the incisors and distal tipping of the molars.

In the vertical plane:

- A check was made for any intrusion or extrusion of the first molars in relation to the palatal plane (U6-CEJ/ANS-PNS). The reference point for the measurements was the respective interface between the cementoenamel junction and the long axis of the tooth.

Statistical analysis, error of method

The arithmetic mean and standard deviation were determined for each variable of the in vitro measurement (forces and moments) and of the in vivo study (analysis of the casts and lateral cephalograms).

Study casts made and lateral cephalograms taken before and after the pendulum appliance therapy were measured or traced and evaluated twice at an interval of three months. If deviations were recorded, the mean value obtained from both measurements was used for further statistical analysis.

The size of the total measurement error (ME) was calculated with the formula $ME = \sqrt{(\Sigma d^2/2n)}$, with d being the difference between the two measurements and n the number of double measurements. The overall ME of the various measurements used in this study was no greater than 0.6 mm or 0.9°. Measuring series designed for calibration of the sensor system have shown that the total error of the electrical measurement was $<2\%$.[27]

RESULTS

In vitro measurement

Details on in vitro measurement are shown in Figures 5 and 6 and Table 2.

When using the Pendulum K with initially applied toe-in bends and uprighting activation plus incorporated distal screw, all forces and moments remained virtually constant over a simulated distalization increment of three mm. The transversal force, Fx, increased from two to 11 cN, and the weakly intrusively acting force, Fy, from six to eight cN. These increases were not statistically significant. The distalization force, Fz, initially 201 cN, was 199 cN after a three-mm distalization increment.

The mesially acting moment, My, rose from 1654 to

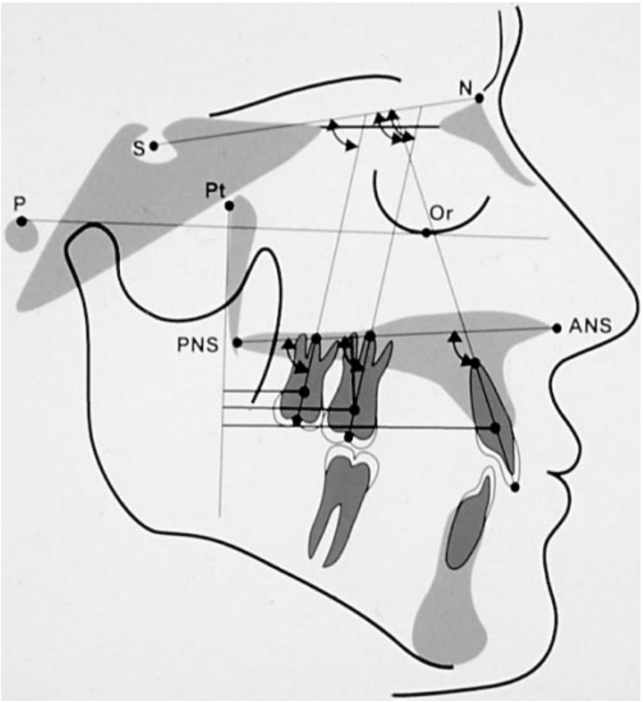

FIGURE 4. Cephalometric analysis (dental changes in the sagittal plane): angles and distances measured cephalometrically before and after molar distalization.

1834 cN mm, whereas the palatally acting moment, Mz, declined slightly from 229 to 164 cN mm. The slight consistent distoinclinatory moment, Mx, also remained virtually constant, rising from the initial 306 to 310 cN mm after three mm.

In vivo study

Measurements of dental casts. The details on the measurement of dental casts are shown in Table 3. Metric analysis of the maxillary casts with respect to the shape of the dental arch revealed that before insertion of the pendulum appliances, the transverse arch width was greater in the region of the second than of the first molar. The mean gain in transverse arch width in the six-year molar region (1.82 ± 1.76 mm between the mb cusps, 1.33 ± 1.53 mm between the central fossae, and 1.16 ± 1.51 mm between the db cusps) illustrates that both expansion and mb rotation took place in that region.

In detail, the mean mb rotation recorded at the six-year molars was 4.54 ± 5.38° on the right and 4.25 ± 5.51° on the left. The corresponding values for the mean increase in transverse arch width at the nonbanded 12-year molars (2.54 ± 1.61 mm between the mb cusps, 2.31 ± 1.18 mm at the central fossae, and 1.84 ± 1.00 mm between the db cusps) confirm also a mean expansion that was greater than that at the banded six-year molars. The nonbanded second molars underwent a mean mb rotation of 2.45 ± 3.89° on the right and 2.08 ± 3.89° on the left. The extent of the rotations was thus lower in the second molars than in the banded six-year molars that were under the influence of the pendulum springs.

Cephalometric analysis. Tables 4 and 5 show details on the cephalometric analysis. The six- and 12-year molars underwent a mean distal tipping of 4.75 ± 4.50° and 6.74 ± 6.25°, respectively, in relation to the palatal plane and of 4.24 ± 4.67° and 6.37 ±

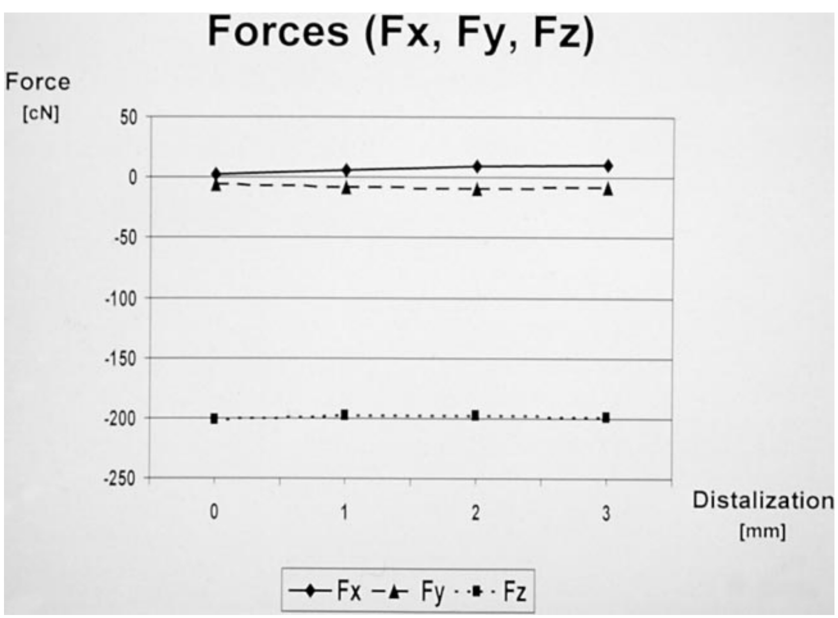

FIGURE 5. Transversal force Fx, vertical force Fy, distalization force Fz (mean values).

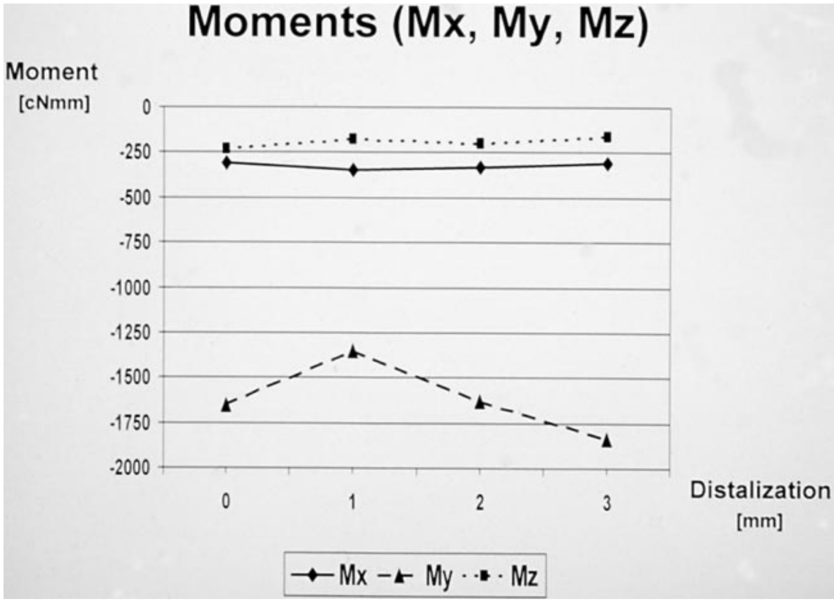

FIGURE 6. Sagittal tipping moment Mx, mesially/distally acting moment My, buccally/palatally acting moment Mz (mean values).

TABLE 1. Molar Distalization With the Pendulum K: Patients, Treatment Time, and Intraoral Activation of the Distal Screw

Number of Patients (n)	Age (Mean)	Treatment Time (Mean)	Activation of Distal Screw (Mean)[a]
66	11 y 8 mo	22	15.3

[a] Ten adjustments of the distal screw yields an additional force application of 50 cN. Screws used: straight-drive sector screws (Forestadent®, article no. 134-1315).

5.57°, respectively, in relation to the anterior cranial base, whereas the upper central incisors were tipped slightly to the labial, ie, 3.13 ± 4.88° to the palatal plane and 3.74 ± 5.11° to the anterior cranial base.

The mean distalization of the six- and 12-year molars was 3.46 ± 1.08 mm and 2.74 ± 0.98 mm, respectively, and the reciprocal protrusion of the incisors 1.26 ± 0.71 mm.

On the basis of the values recorded for the six-year molars, their mean distalization distance of 3.46 ± 1.08 mm represented 73.53% of total movement in the sagittal plane, whereas a mean mesial incisor movement of 1.26 ± 0.71 mm represented an anchorage loss of 26.47%. The mean first molar extrusion in the vertical plane was 0.39 ± 0.80 mm.

DISCUSSION

The standard pendulum appliance, the Pendulum K, has been modified by changing the location of the 0.032 inch TMA® springs in the posterior region of the six-year molars that are to be distalized by adding a distal screw and by the initial application of uprighting activation and a toe-in bend at the end of the pendulum. These modifications are aimed at preventing palatal movements and distal tippings of the first molars.

As shown by the results of the in vitro analysis, all forces and moments remain virtually constant under continuous activation of the distal screw (10 activations per mm) over a simulated distalization increment of three mm. In the sagittal plane, a continuously acting distalization force combined with a low, consistent distoinclinatory moment permits almost bodily tooth movement. A slight, buccally directed force and a mesially outward rotating moment prevent therapeutically

TABLE 2. Forces and Moments Measured In Vitro at the Pendulum K (Means and Standard Deviations)

Forces F (cN)/Moments M (cN mm)	N	0 mm (Mean)	0 mm (SD)	1 mm (Mean)	1 mm (SD)	2 mm (Mean)	2 mm (SD)	3 mm (Mean)	3 mm (SD)
Fx (transversal force)	24	2	3	6	5	9	11	11	14
My (mesially/distally acting moment)	24	−1654	869	−1353	842	−1633	1107	−1834	1265
Fy (vertical force)	24	−6	17	−8	18	−9	19	−8	21
Mz (bucally/palatally acting moment)	24	−229	398	−175	368	−202	414	−164	471
Fz (distalization force)	24	−201	5	−198	3	−198	3	−199	2
Mx (sagittal tipping moment)	24	−306	484	−346	517	−334	517	−310	646

TABLE 3. Changes in Molar Position Induced by Pendulum Appliance Therapy in the Horizontal Plane (Cast Analysis)

Type of Measurement	N	T1 (Mean)	T1 (SD)	T2 (Mean)	T2 (SD)	ΔT1 − T2 Mean	ΔT1 − T2 SD
Mesiobuccal cusp tips (mb)[a]							
UR6-UL6 (mm)	66	50.50	3.24	52.33	3.04	−1.82	1.76
UR7-UL7 (mm)	19	55.24	3.43	57.78	3.69	−2.54	1.61
Central fossa (cf)[a]							
UR6-UL6 (mm)	66	45.64	2.98	46.97	2.93	−1.33	1.53
UR7-UL7 (mm)	19	49.54	3.14	51.14	3.54	−2.31	1.18
Distobuccal cusp tips (db)[a]							
UR6-UL6 (mm)	66	52.98	3.05	54.14	3.07	−1.16	1.51
UR7-UL7 (mm)	19	55.57	3.88	57.41	4.15	−1.84	1.00
Tooth UR6 rotation (°)[b]	66	14.39	6.73	9.85	6.76	4.54	5.38
Tooth UL6 rotation (°)[b]	66	13.20	6.31	8.95	7.56	4.25	5.51
Tooth UR7 rotation (°)[b]	19	4.24	7.08	1.79	5.55	2.45	3.89
Tooth UL7 rotation (°)[b]	19	3.45	7.68	1.47	7.76	2.08	3.89

[a] For ΔT1 − T2: value before distalization − value after distalization; positive value = decrease, negative value = increase.
[b] Determination of type of molar rotation: angle between midpalatal raphe (MPR) and a line running between the mesiobuccal and distobuccal cusps of the molars; ΔT1 − T2: value before distalization − value after distalization; positive value: mesiobuccal rotation; negative value: distobuccal rotation.

TABLE 4. Dental Changes During Pendulum Appliance Therapy in the Sagittal Plane (Cephalometric Analysis)

Type of Measurement	N	T1 (Mean)	T1 (SD)	T2 (Mean)	T2 (SD)	δT1–T2 (Mean)	δT1–T2 (SD)
Dental-linear							
U1-CEJ/PTV (mm)	66	50.32	3.96	51.58	3.82	−1.26	0.71
U6-CEJ/PTV (mm)	66	20.05	3.13	16.59	3.44	3.46	1.80
U6-CEJ/ANS-PNS (mm)	66	13.09	1.97	13.48	2.16	−0.39	0.80
U7-CEJ/PTV (mm)	19	14.74	2.79	12.00	2.73	2.74	0.98
Dental-angular							
U1/ANS-PNS (°)	66	108.07	6.61	111.20	7.07	−3.13	4.88
U1/SN (°)	66	100.78	6.56	104.52	7.30	−3.74	5.11
U6/ANS-PNS (°)	66	75.22	5.17	70.47	6.23	4.75	4.50
U6/SN (°)	66	67.85	5.46	63.61	6.36	4.24	4.67
U7/ANS-PNS (°)	19	67.71	6.55	60.97	6.31	6.74	6.25
U7/SN (°)	19	66.21	6.10	54.84	7.23	6.37	5.57

TABLE 5. Proportion of Maxillary Molar Distalization in Total Movement in the Sagittal Plane (Cephalometric Analysis)

Type of Measurement	N	ΔT1 − T2 (Mean)	ΔT1 − T2 (SD)
Dental-linear (mm)			
1-CEJ/PTV	66	−1.26	0.71
6-CEJ/PTV	66	3.46	1.08
Total sagittal movement[a]	66	4.72	1.12
Calculation of ratio (%)			
Proportion of molar distalization in total movement[b]	66	73.53	14.08

[a] Total movement in the sagittal plane = [1-CEJ/PTV] + [6-CEJ/PTV].
[b] Calculation: proportion of molar distalization in total sagittal movement = 100 × (6-CEJ/PTV)/([1-CEJ/PTV] + [6-CEJ/PTV]).

undesirable palatal movements in the transverse plane and induce derotation of the drifted six-year molars that have been rotated mesially inward around the palatal root.

The findings of this in vitro study confirm that the Pendulum K is suitable for clinical application. In ideal cases, this modified pendulum appliance requires no intraoral reactivations at the pendulum springs. The therapeutically required forces and moments can be selectively activated by adjusting the distal screw, and

TABLE 6. In Vivo Studies Relating to Pendulum Appliance Therapy: Comparison of the Dental-linear and Dental-angular Changes in the First Molar Positions in the Sagittal Plane (Cephalometric Analysis) and Changes in the Dental Arches in the First Molar Region in the Horizontal Plane (Cast Analysis)[a]; Some Values Rounded Off[b]

Studies	Pendulum Appliance	n	Distal Movement, First Molar (mm)	Distal Tipping First Molar (°)	Intrusion (−)/ Extrusion (+) First Molar (mm)	Effective Molar Distalization (%)	Rotation, First Molar (°)[c]	Transversal Width of Dental Arch in First Molar Region[d] (mm)
Ghosh and Nanda[6]	Hilgers pendulum	41	3.4	8.4 (SN)	−0.1 (ANS-PNS)	56.9	—	1.4 (mb) 0(db)
Byloff and Darendeliler[7]	Hilgers pendulum	13	3.4	14.5 (ANS-PNS)	−1.7 (ANS-PNS)	70.9	—	—
Byloff et al.[8]	Pendulum with uprighting bends	20	4.1	6.1 (ANS-PNS)	−1.4 (ANS-PNS)	64.2	—	—
Kinzinger et al.[11]	Pendulum K	50	2.9	3.1 (ANS-PNS) 3.2 (SN)	0.4 (ANS-PNS)	72.5	—	1.7 (mb) 1.0 (db)
Bussick and McNamara[14]	Hilgers pendulum	101	5.7	10.6 (FH)	−0.1 (ANS-PNS)	76	—	—
Joseph and Butchart[15]	Hilgers pendulum	7	5.1	15.7 (ANS-PNS)	0.6 (ANS-PNS)	57.9	—	—
Chaques-Asensi and Kalra[17]	Hilgers pendulum	26	5.3	13.1 (SN)	−1.2 (ANS-PNS)	70.6 (M to PM)	—	—
Kinzinger et al.[21]	Pendulum K	20	3.4	5.2 (ANS-PNS)	—	70.3	16:3.7 26:4.1	1.2 (cf)
Kinzinger et al.[23]	Pendulum K	36	3.1	3.3 (ANS-PNS) 3.1 (SN)	0.6 (ANS-PNS)	70.3	16:5.2 26:4.3	2.1 (mb) 1.8 (cf) 1.7 (db)
Kinzinger et al.[25]	Pendulum K	30	3.9	4.2 (ANS-PNS) 4.6 (SN)	−0.2 (ANS-PNS)	76.3 (M to PM)/ 74.2 (M to 1)	—	—
Kinzinger et al, this study	Pendulum K	66	3.5	4.7 (ANS-PNS) 4.2 (SN)	0.4 (ANS-PNS)	73.5	16:4.5 26:4.3	1.8 (mb) 1.3 (cf) 1.2 (db)

[a] *References 6–8,11, 14, 15, 17, 21, 23, 25.*
[b] Reference planes: ANS-PNS, palatal plane; SN, anterior cranial base; FH, Frankfort horizontal.
[c] Positive value, mesiobuccal or distolingual rotation; negative value, distobuccal or mesiolingual rotation.
[d] Positive value, increase; negative value, decrease; measuring points: mb, mesiobuccal cusp tips; cf, central fossa; db, distobuccal cusp tips.

the extent of screw activation is variable and depends on the findings. The distal screw can be activated either by the orthodontist at the regular checkups or, preferably, by the patient himself at shorter intervals.

Analysis of the cast measurements reveals that a therapeutically desirable mesial outward molar rotation and a transversal expansion of the dental arch had occurred. The quality and quantity of molar distalization and of reactive incisor protrusion are in direct correlation with the patient's dental age. For example, the values for upper molar distalization and tipping are comparatively higher in the early mixed dentition than in the permanent dentition, whereas mesial incisor movement is less pronounced.[21,25]

These phenomena can be explained by the respective developmental stage of the second molars. If the second molars are still unerupted, they offer less resistance and act like a fulcrum on the six-year molars that are to be distalized. During distalization, the first molar is tipped across the unerupted second molar. With increasing root formation and eruption of the 12-year molars, the contact point between the molars continuously is displaced coronally. The first molar is consequently confronted with greater resistance, and the tipping tendency of the tooth is reduced. The amount of distalization is smaller and the mesial movement of the anterior segment larger. Overall, this results in a decrease in the proportion represented by molar distalization in total movement with increasing age.[21]

Studies published to date on various types of pendulum appliance* show major differences in the quality of molar movement (Table 6). As shown in this study and in previous studies,[11,21,23,25] the Pendulum K permits almost translatory molar distalization with distal tippings ranging from 3.1° to 5.2°. Also, when a standard pendulum appliance was used with subsequent uprighting activation, only distal tips of the first molars by 6.1° were recorded.[8] However, when the standard pendulum appliance according to Hilgers was used without uprighting activation in the region of the pendulum springs, pronounced molar tipping of up to 14.5°[7] and 15.7°[15] were registered. The proportion of molar distalization in total movement ranged from 56.9%[6] to 76.3%.[25]

CONCLUSIONS

The results of the in vitro analysis were confirmed by those of the in vitro study with its collective of 66 patients. The Pendulum K permitted extensive translatory molar distalization with minimum tipping of the tooth crowns. The initial uprighting activation at the end of the pendulum resulted in an intrusive force with an uprighting moment applied to the molar roots. A toe-in bend is appropriate for the derotation of molars that have drifted because of mesial-inward rotation. Regular adjustment of the incorporated distal screw led to a displacement of the rotational center points of the pendulum springs and continuous reactivation of the applied forces and moments. Through the described modifications, the Pendulum K helps prevent undesirable side effects such as pronounced distal tipping and palatal movements of the molars. The proportion of molar distalization in total movement was more than 70%.

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