

Biomechanics of a modified Pendulum appliance—theoretical considerations and *in vitro* analysis of the force systems

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SUMMARY The aim of this study was to analyse the acting forces and moments induced by a special orthodontic appliance, the Pendulum K, for molar distalization in the transverse and sagittal planes.

The purpose-designed test set-up (artificial maxilla with anchorage unit and two electrothermodynamic molars, an electronic measuring unit, a unit with force–moment sensor, an analogue/digital converter, and a data read-out unit) allowed simulation of *in vivo* conditions on the one hand and precise determination of the force systems on the other. The appliances investigated were three specimens of the Pendulum K.

In vitro measurement of the resulting force systems revealed that the forces and moments in the transverse and sagittal planes remained almost constant over a 3 mm measuring increment when the distal screw was continuously activated (10 activations/mm). Without reactivation of the incorporated distal screw, however, a marked decline in the force systems was recorded.

The Pendulum K allows translatory distalization of the upper molars and thus dental arch expansion, dispensing with the need for permanent teeth to be extracted, subject to a corresponding indication. This is achieved by continuous adjustment of an incorporated distal screw and by specific pre-activations of the Pendulum springs.

Introduction

Orthodontic correction of mesial drifting of buccal teeth in the maxilla is one of the most frequent tasks for orthodontists. In this context, sagittal expansion of the dental arch through distalization of teeth is indicated in patients with a neutro-basal jaw base relationship if the extraction of permanent teeth is to be avoided. All appliances traditionally used for upper molar distalization have been compliance dependent. However, concerns about wear time and aesthetic impairment have resulted in the increasing use of exclusively intraoral appliances which are largely independent of patient compliance. In particular, different Pendulum appliances (e.g. Hilgers, 1992; Snodgrass, 1996; Byloff *et al.*, 1997, 2000; Kinzinger *et al.*, 2000, 2002) have proven satisfactory in clinical application. The standard appliance introduced by Hilgers (1992), however, gives rise to the following appliance-specific problem: once the activated Pendulum springs (0.032-inch titanium molybdenum alloy (TMA) wire, Ormco Corp., Glendora, California, USA) have been inserted into the palatal sheaths of the molar bands, the molars are moved on Pendulum-like arc radii. The potential consequences are palatal movement of the molars and tipping of the dental crowns. The present modification, the Pendulum K, is aimed at preventing these negative side effects through the incorporation of a distal screw into the base of the appliance and the application of uprighting activation and a toe-in bend in the region of the springs. Although a number of clinical studies have been published (Kinzinger *et al.*, 2000, 2003a,b, 2004, 2005, 2006), exact data on the acting forces and moments cannot be derived

from their findings. If the appliance is fixed intraorally, this is, in biomechanical terms, a multiple statically indeterminate system for which an assessment of the activating forces and moments is currently not feasible.

The aim of the present *in vitro* study was to analyse the acting forces and moments induced by the Pendulum K in the transverse and sagittal planes.

Materials and methods

The test set-up was based on the following components: an artificial maxilla of pressurized polymer with 10 rigidly fixed teeth constituting the anchorage unit, two electrothermodynamic molars (Rhee *et al.*, 2001), an electronic measuring unit for thermal control and regulation, a unit with a force–moment sensor, an analogue/digital converter, and a data read-out unit (Rosarius *et al.*, 1996; Friedrich *et al.*, 1998, 1999).

For the measuring procedure, pre-fabricated orthodontic metal bands, each of which had a special bracket (Dentaurum, Ispringen, Germany), were laser welded onto the buccal face of the molars. At the start of the measuring procedure, the three-dimensional sensor was connected to the sheath section of the special bracket by means of a clamping device and then maintained in this position relative to the molar by using a retaining device. The measuring sensor, as the central element of the measuring apparatus, registered the forces and moments simultaneously with a range up to 10 N/100 Nmm and a resolution of 0.05 N/0.1 Nmm. The measuring signals were digitized in the read-out unit and

converted by means of the calibration matrix into force and moment components, which were then processed in a mobile measuring computer.

Three specimens of each Pendulum K (Figure 1) were produced in the dental laboratory. This modification comprised an orthodontic screw [straight-drive sector screws (Forestadent, Pforzheim, Germany, order no. 134-1315)] dividing the acrylic pelot, in turn, into two parts. The anterior part connects four anchorage teeth via wire retainers where it is temporarily fixed with tooth-coloured composite. The posterior part comprised the Pendulum springs and, thus, the active elements of the appliance. Prior to insertion, these springs were three-dimensionally pre-activated by applying certain bends. When integrated in the mouth, the appliance may be reactivated by turning the distal screws without having to detach the Pendulum springs from the palatal molar sheaths.

For this *in vitro* study, the appliances were rigidly screwed to the artificial maxilla. The distal screw incorporated into the Nance button of the Pendulum K was not adjusted during the first measuring series but was continually adjusted during the second series (10 times per simulated 1 mm distalization increment). The measured parameters were the force systems transmitted to the first molars by the springs after pre-activation with a distalization force of 2 N as well as with an activation to upright the roots and a toe-in bend. The forces and moments were registered in all three planes at baseline and after distalization increments of 1, 2, and 3 mm. Each appliance was measured eight times on each side (four times without and four times with adjustment of the distal screw).

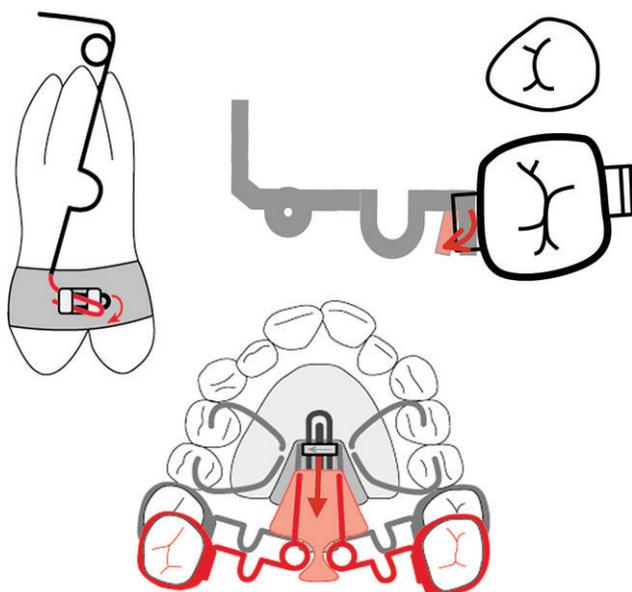


Figure 1 Schematic representation of the Pendulum K with distal screw, integrated uprighting activation (20 degrees), toe-in bend (10 degrees), and distal activation (200 cN) in the Pendulum spring region for bilateral molar distalization.

The components, tooth, band, and palatal sheath, were regarded as rigid. As the centre point of the sensor coordinate system was not identical with that of the force application point of the springs at the palatal sheath of the molar band, the moment data had to be converted. It has to be borne in mind that the dentition of the artificial maxilla ended with the 6-year molars, second and third molars being absent. The first molars could thus be moved under the influence of the pre-activated springs without interference from the distally adjacent teeth. Reactive forces and moments on the anchorage unit were not measured.

The data from the measuring series were registered and stored in the data read-out unit. To facilitate interpretation of the results and for biomechanical analysis, the system of co-ordinates and the convention governing signs were selected in accordance with the recommendations of Burstone and Koenig (1974). This means that all mesially or buccally directed forces and all moments that induce mesially inward rotating moments of the tooth crown as well as uprighting of the root have a positive sign. All contrary, distally, or lingually directed forces and moments that cause mesially outward rotation or sagittally tipping crown movements have a negative sign. The x -axis shows tooth movement in the transverse plane, and the z -axis movement in the sagittal plane.

The arithmetic mean was determined for each variable of the *in vitro* measurement (forces and moments). Measuring series, designed for calibration of the sensor system, have shown that the total error of the electrical measurement is less than 2 per cent (Rosarius *et al.*, 1996). The calibration is maintained up to a load of 350 N/2500 Nmm.

Results

For ease of understanding, the results obtained from the measuring series are presented below as absolute figures. In Tables 1 and 2, and Figures 2 and 3, however, the values are listed according to the conventions governing the use of leading plus and minus signs.

In the first measuring series, activations were confined to the spring region (initially applied toe-in bend, uprighting activation, distal activation). Over the measured distance, a marked decrease in distalization force from the initial value of 2.01 to 0.80 N was registered. The level and direction of the transverse force, F_x , changed from 0.05 N buccal to 0.18 N palatal.

The sagittal tipping moment, M_x , increased from 4.52 to 11.36 Nmm, while the mesially outward rotating moment, M_y , underwent a marked decrease from 16.53 to 7.23 Nmm.

In the second measuring series, pre-activation of the springs was supplemented by continuous adjustment of the distal screw incorporated in the base of the Nance button. As the results show, all forces and moments remained almost constant over a simulated distalization increment of

Table 1 Measuring series 1: forces and moments in the *in vitro* measurement of the Pendulum K without distal screw activation [means and standard deviations (SDs)].

Forces F (cN)/ Moments M (cNmm)	n	0 mm		1 mm		2 mm		3 mm	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
Transverse plane									
Fx (transverse force)	24	0.05	0.08	-0.05	0.08	-0.16	0.07	-0.18	0.09
My (mesially/ distally rotating moment)	24	-16.53	7.48	-12.39	8.39	-10.95	7.91	-7.23	6.46
Sagittal plane									
Fz (distalization force)	24	-2.01	0.05	-1.61	0.16	-1.15	0.15	-0.80	0.16
Mx (sagittal tipping moment)	24	-4.52	4.49	-6.36	4.58	-9.73	7.23	-11.36	9.39

Table 2 Measuring series 2: forces and moments in the *in vitro* measurement of the Pendulum K with continuous distal screw activation* [means and standard deviations (SDs)].

Forces F (cN)/Moments M (cNmm)	n	0 mm		1 mm		2 mm		3 mm	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
Transverse plane									
Fx (transverse force)	24	0.02	0.03	0.06	0.05	0.09	0.11	0.11	0.14
My (mesially/distally rotating moment)	24	-16.54	8.69	-13.53	8.42	-16.33	11.07	-18.34	12.65
Sagittal plane									
Fz (distalization force)	24	-2.01	0.05	-1.98	0.03	-1.98	0.03	-1.99	0.02
Mx (sagittal tipping moment)	24	-3.06	4.84	-3.46	5.17	-3.34	5.71	-3.10	6.46

*Ten adjustments of the distal screw result in an additional force application of 50 cN.

3 mm. The transversely directed force, Fx, increased slightly from 0.02 to 0.11 N. The distalization force, Fz, initially 2.01, was 1.99 N after the 3 mm distalization increment.

The mesially de-rotating moment My increased very slightly from 16.54 to 18.34 Nmm. The slight sagittal tipping moment, Mx, also remained virtually constant, rising from the initial 3.06 to 3.10 Nmm after 3 mm.

Discussion

Biomechanics of orthodontic tooth movement

The application of an orthodontic force leads to an initial periodontal displacement of the tooth and therefore to alveolar deformation and compression of the periodontal ligament (PDL), followed by reactive remodelling of the PDL and bone by resorption and apposition. In both phases, the PDL plays a key role; it has the double function of transmitting the forces to the bone and contributing to the alteration of alveolar bone (Luder, 1990).

From a clinical point of view, the choice of force system and the optimum force magnitude are the decisive factors for obtaining the desired tooth movement (Burstone, 2000).

The ideal orthodontic tooth movement should be translatory, as histological and clinical studies as well as finite-element analysis have shown that due to the even surface distribution of the force applied, bodily tooth movement causes less damage to the hard tissues than tipping movement (Reitan, 1957, 1964, 1974, 1985; Plets *et al.*, 1974; Jonas, 1980; Hocevar, 1981; McGuinness *et al.*, 1991; Wehrbein and Diedrich, 1992). Regarding the force magnitude, continuous forces of approximately 0.2 to 0.3 N/cm² of root surface are considered to be optimal, as this pressure does not exceed capillary blood pressure and, therefore, blood supply to the periodontium is maintained. Excessive forces might cause resorption of the roots, tissue damage, and pain. According to Ricketts *et al.* (1979), a maxillary molar has an average root surface of 1.20 cm². If forces of 1.5–2 N/cm², as recommended by Ricketts *et al.* (1979), are considered, a force between 1.8 and 2.4 N is ideal for translatory sagittal movement. The total of the root surfaces in the anchorage unit exposed to the applied force has to be determined individually but has to be at least three to four times greater than the root surface of the tooth to be distalized. For this study, a distalizing force magnitude of 2 N was chosen.

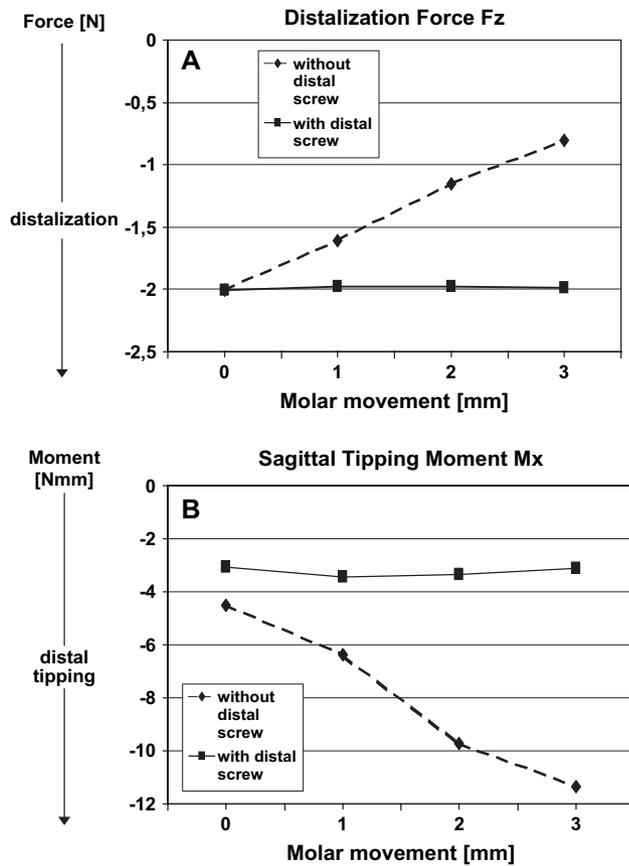


Figure 2 Forces and moments in the sagittal plane, z-axis (mean values). (A) Distalization force Fz (B) Sagittal tipping moment Mx.

Biomechanics of the Pendulum appliances

The standard Pendulum appliance introduced by Hilgers (1992) consists of an acrylic palatal plate to which a total of four steel wire retainers and two TMA[®] springs are fastened as active elements. Once the Pendulum springs have been activated, their ends are inserted into palatal sheaths on the molar bands, causing the molars to be moved on given Pendulum-like arc radii in the transverse and sagittal planes. The side-effects included palatal movement of the molars, to a tendency for crossbite in the transverse plane, and distal tipping of the crowns in the sagittal plane.

For the Pendulum K, the standard Pendulum appliance was modified with a positional change of the 0.032-inch TMA[®] springs, the addition of a distal screw, and the initial application of uprighting activation and toe-in bends at the end of the Pendulum. These modifications were aimed at preventing palatal movements and distal tipping of the first molars, as described in the following section.

Transverse plane

A force, $-F_p$, is applied at the palatal sheath on the molar band by the springs which are pre-activated with a

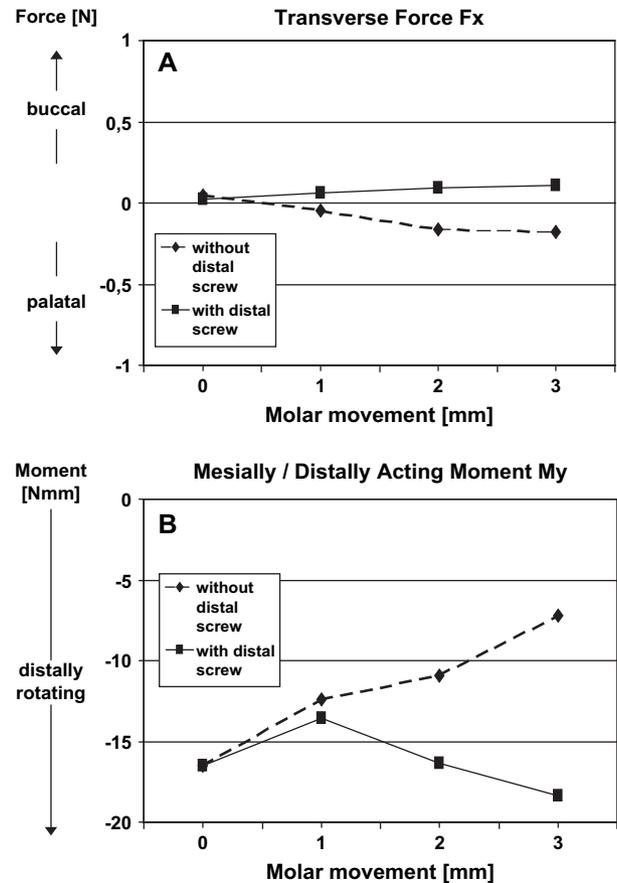


Figure 3 Forces and moments in the transverse plane, x-axis (mean values). (A) Transverse force Fx (B) Mesially/distally rotating moment My.

distalization force (Figure 4A). This distalization force, $-F_p$ is counteracted by an opposing force F_A . This opposing force has to be intercepted as far as possible by the anchorage unit (hard palate, anchorage teeth) in order to prevent undesirable side-effects (mesial movement of the anchorage teeth).

At the same time, a disto-buccal rotating moment, M_p , resulting from the product of the force $-F_p$ and the horizontal distance from the centre of resistance (CR_e) of the molar, is exerted. The direction of the force $-F_p$ depends directly on the course of the arc described by the spring. The special location of the closed loop of the spring, which is the centre of rotation (CR_{ot}), slightly distally from the CR_e, and the activation of the distal screw, performed ideally at the zenith of the arc, result in the following features with respect to the force line to distal and the force–moment ratios in the palatal sheath.

Up to the zenith of the arc, the force $-F_p$ applied by the spring can be divided into two vectors, one directed distally and the other buccally. The resulting force line runs disto-buccally and has, in the region of the palatal sheath, the same direction and effect as would be

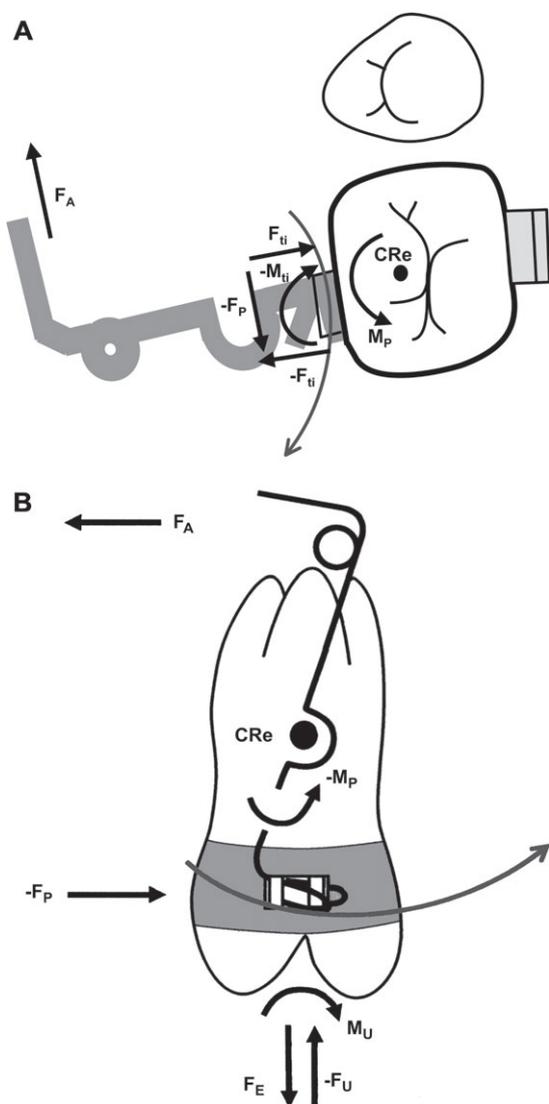


Figure 4 Biomechanical approach to the systems to be differentiated in the transverse and sagittal planes. First molar distalization induced by the Pendulum springs in the (A) transverse and (B) sagittal planes.

induced by a toe-in bend as a first-order activation. An additional toe-in bend, bent directly into the spring generates a force in the mesio-buccal direction at the first molar and a moment, $-M_{ti}$, that counteracts the disto-buccal moment M_p .

Since the Pendulum loops, as CRot, are located distally of the CRe of the molars because a toe-in bend is applied at the end of the Pendulum, the molars are initially de-rotated and distalized by the appliance which is activated at approximately 2 N. The outcome is a slightly increased intermolar distance. The intraoral reactivation of the distal screw effects a distal displacement of the horizontal CRot, resulting in modification or readjustment of the arc on which the tooth is moved. The outcome is a largely linear molar distalization.

Due to the specific biomechanics of the appliance, the first molar thus undergoes a desired expansion and distalization as well as mesio-buccal rotation. In ideal cases, there is no palatal molar movement.

Sagittal plane

The force, $-F_p$, applied by the springs to the first molars acts coronally from the CRe (Figure 4B). The tooth to be distalized is extruded in the sagittal plane through the Pendulum-like distalization path running convexly towards occlusal and distal tipping of the crown through the resulting moment, $-M_p$.

The application of an uprighting activation at the end of the Pendulum causes an intrusive force, $-F_U$, on the molars; this force counteracts the extrusive force F_E caused by the arc described by the spring. The uprighting activation moreover causes an uprighting moment M_U to act on the molar roots.

In order to allow maximum distal bodily movement of the 6-year molars, the vertical forces, F_E and F_U , should be equal and thus neutralize each other. At the same time, the sum of all moments should be zero. For this purpose, the moment, M_A , caused by the uprighting activation should ideally be equal to the distal tipping moment, $-M_p$.

Activation of the distal screw allows displacement of the posterior portion of the palatal pelot containing the springs. Their CRots are consequently moved continuously distally, resulting in continuous reactivation of the force systems described above.

The findings of the present *in vitro* study confirm the theoretical consideration on the suitability of the Pendulum K as an orthodontic appliance for bodily molar distalization. Specific pre-activations in the spring region in conjunction with continuous activation of the distal screw integrated in the appliance allow almost translatory tooth movement in both the transverse and the sagittal plane, despite the given arcs.

First experiences in clinical treatment with the Pendulum K

The results of the *in vitro* analysis have been confirmed by a number of *in vivo* studies (Kinzinger *et al.*, 2000, 2003a,b, 2004, 2005, 2006). The Pendulum K allows extensive translatory molar distalization with minimum tipping of the tooth crowns (Figure 5). The initial uprighting activation at the end of the Pendulum results in an intrusive force and an uprighting moment being applied to the molar roots. A toe-in bend is appropriate for the de-rotation of molars that have drifted due to mesial-inward rotation. Regular adjustment of the incorporated distal screw leads to a displacement of the rotational centre points of the springs and continuous reactivation of the applied forces and moments. The extent of screw activation is variable and depends on the findings. The distal screw should be activated by the orthodontist at

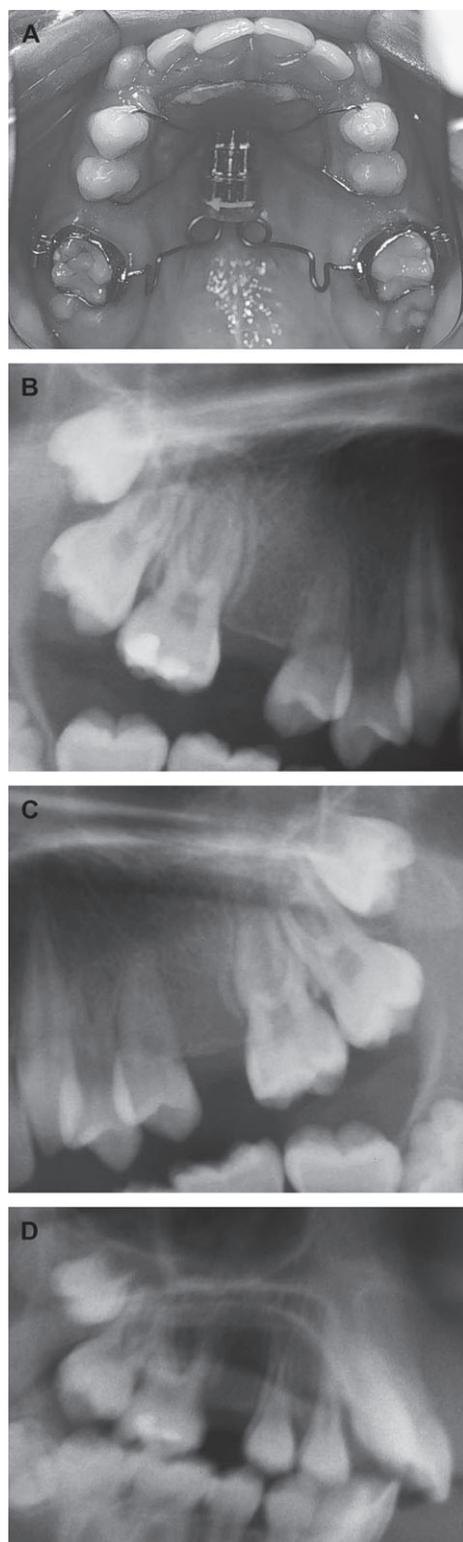


Figure 5 Treatment example. The anterior part of the acrylic pelot of the appliance serves as anchorage and is temporarily fixed via wire retainers at four anchorage teeth by means of tooth-coloured composite; the posterior part comprises the Pendulum springs as the active elements of the appliance. By activation of the Pendulum springs, the first molars were distalized (A). Dental pantomographs (B, C) and lateral cephalogram (D) showing that bodily molar distalization occurred.

the regular check-ups, so the Pendulum K is used as a non-compliance appliance. Exceptionally, the patients, or one of their parents, may turn the screw at shorter intervals. Ideally, the Pendulum K requires no intraoral reactivations at the springs. Through the described modifications, the Pendulum K helps prevent therapeutically undesirable side-effects such as pronounced distal tipping and palatal movements of the molars.

Studies published to date show that the Pendulum K also allows translatory molar distalization with distal tipplings ranging from 3.1 to 5.2 degrees (Kinzinger *et al.*, 2003b, 2004). Analysis of the cast measurements reveals that a therapeutically desirable mesial-outward molar rotation and a transverse expansion of the dental arch, to avoid crossbites, occur (Kinzinger *et al.*, 2000).

When using the appliance, attention should be paid to the following. In some cases, temporary inflammations of the palatal mucosa were observed, which disappeared after removal of the appliance. No pressure ulcers or other complications occurred. Primary molars and premolars are suitable for intraoral anchorage when using a Pendulum appliance for molar distalization, but the values of reactive mesial incisor movement and protrusion are comparatively higher in the early mixed than in the permanent dentition (Kinzinger *et al.*, 2005). Also the quality and quantity of molar distalization are in direct correlation with the patient's dental age. These phenomena can be explained by the respective developmental stage of the second molars (Kinzinger *et al.*, 2004): if they have not erupted yet, they offer less resistance and act like a fulcrum on the 6-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 second molars, the contact point between the molars is displaced continuously 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.

Conclusions

This new type of orthodontic device is a suitable appliance, in terms of its biomechanics, to treat patients with a dento-alveolar Class II malocclusion as well as with a sagittal arch length discrepancy. When physiological force magnitudes are applied, it allows molar distalization that is independent of patient co-operation.

The theoretical considerations on the biomechanics of the Pendulum appliance were confirmed as follows by the *in vitro* study:

1. The Pendulum K allows largely translatory molar distalization. Its specific biomechanics lend themselves to the correction or prevention of pronounced distal tipping and palatal movement.

2. The uprighting activation causes an uprighting moment to act on the molar roots.
3. A toe-in bend can be used for de-rotating molars that have rotated mesially inwardly and for neutralizing a counteracting moment caused by the applied force acting palatally from the CRe of the molar.
4. The principle of displacing the CRot of the springs distally by incorporating an adjustable screw results in continuous reactivation of the applied forces and moments.

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