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High-resolution in vivo measurement of biomechanical features of the periodontium

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Common models describing initial tooth movement mostly rest on the assumption of viscoelastic behaviour of the tooth. The periodontium is regarded as an elastic isotropic material following Hooke's law for small displacements. These assumptions have been examined in vivo. The study is based on 22 cases with natural spacing between the teeth. An experimental device was designed for measuring small mesial and distal rotations of the crown following time-dependent torques. They were optically recorded with high accuracy (<0.001 deg resolution). The torques were produced by a digitally-controlled rotary magnet motor and applied to the buccal side of mandibular premolars by means of a flexible Cardan shaft. Thresholds were found which had to be overcome by the applied torque to rotate the tooth about its centre of resistance. The data provided strong hints that the periodontium was a thixotropic substance and showed also shear thinning. These properties seemed to have a large interindividual variety.

Key words: initial tooth movement, in vivo measurement, thixotropic periodontium

1. Introduction

The predictability of orthodontic tooth movement following the force and/or torque applied is a goal of orthodontic research. Apart from biochemical processes during bone-remodelling, the biomechanical understanding of initial tooth movement

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(better: displacement) is an initial step. The biomechanical properties of the periodontal ligament (PDL) were the subject of numerous in vitro [1]–[7] and in vivo [8]–[10] studies. The numerical models used for the evaluation of the measuring data or for finite element calculations commonly assumed the following general characteristics of the PDL:

1. The delayed tooth displacement after application of force and/or torque was attributed to viscoelasticity [3], [10], [11].

2. The viscosity parameters were assumed to be independent of the force or torque applied [12].

3. With regard to the elastic component, the PDL was said to show a strain–stress characteristic of a sigmoidal shape, hence for small stresses Hooke's law was expected [2], [3], [5].

4. For the FE-calculations, the PDL was assumed to be viscoelastically isotropic [6], [7], [13].

These assumptions seemed to be inapplicable for the following reasons:

i) The PDL is not a simple viscoelastic layer, but a biphasic system. A plexus of blood vessels, lymphatic ducts, nerves and tissue fluid are situated between the (visco-) elastic fibres of the PDL, which anchors the tooth with the alveolar bone [14]. This plexus along with the tissue fluid must not be modelled as a Newtonian fluid. Their mechanical properties rather correspond to those of a gel.

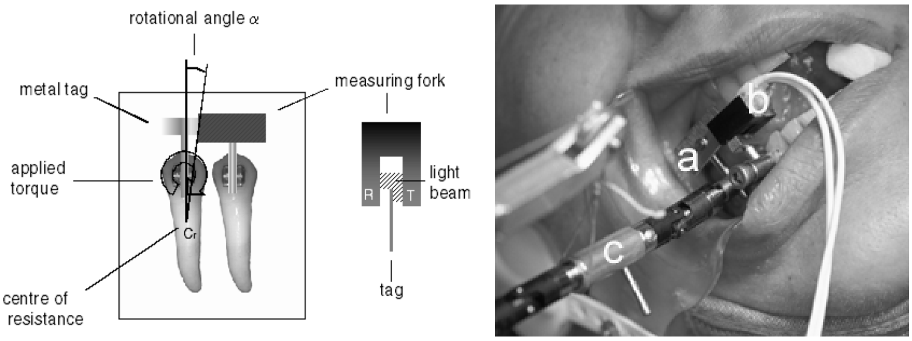
ii) Certainly every tooth displacement physically leads to a strain distribution within the periodontal ligament (PDL), and the corresponding local deformation at the interface of PDL–alveolar bone causes a distribution of normal and shearing tension over this interface produced especially by the tensed fibres which is said to be the local stimulus for bone remodelling responsible for a permanent orthodontic tooth displacement [13], [15], [16]. But vice versa, small permanent external force systems, e.g., the tongue pressure, acting on the teeth must not result in their displacements, since for this the stimulation of bone remodelling is inappropriate. Therefore we expect that teeth cannot be displaced by small external forces or torques, since in this case the gel-like plexus and gel-like tissue fluid show an extremely high viscosity. Only when the forces or torques exceed certain thresholds does the effect of shear thinning diminish the viscosity, so that tooth displacements become possible.

To check these expectations we had to scrutinize the strain–stress characteristics of tooth movements in vivo under very small external stresses. Therefore, we designed an apparatus for in vivo measuring very small tooth displacements at extremely high resolution and accuracy on condition that the effort and time frame were acceptable for the subjects. In the following we describe the conception and properties of this apparatus and the measurements carried out with it.

2. Method and material

2.1. Measuring method

In vivo, pure torques (force couples) were applied approximately perpendicularly to the buccal surface of mandibular premolars. They were generated by a digitally controlled rotary magnet motor (±1.43 Ncm). The motor shaft was connected to the premolar by a flexible Cardan shaft (figure 1). In orthodontics, it is a common experience that the soft suspension, the PDL, by which a tooth is flexibly linked to the alveolar bone, possesses a centre of resistance C_R whose approximation is good. The buccally-lingually directed pure torque thus produced a rotation of the tooth about the axis which was parallel to the torque and ran through C_R [2], [4]. In premolars, the centre C_R lies about one third of the length of tooth root below the crest of the alveolar bone. Thus, depending on the sign, the rotation made the tooth crown to shift mesially or distally. To record these displacements a measuring fork was mounted on the crown of the neighbouring tooth. The fork absorbed a light beam flowing from a transmitter and to a receiver. A metal tag mounted on the rotating tooth modulated the light flux. The thus measured displacement D of the tag was proportional to the rotational angle α of the tooth (max. 0.17 deg).



a) b)

Fig. 1. The pure torque was applied to the test tooth via the bracket. Depending on its sign, the metal tag was shifted into or out of the measuring fork, and modulated the light flow from the light transmitter (T) to the receiver (R) (a). Photo (b): The metal tag (a) was mounted on the test tooth, the measuring fork (b) on the adjacent tooth (reference); the cardan shaft (c) was used for torque transmission

The series of rotational angle–time functions $\alpha(t)$ were measured following the series of special torque–time functions $T(t)$. The individual time function $T(t)$ was digitally controlled via the magnet motor. Starting from zero $T(t)$ progressed to a final value in a linear function, then remained constant, and was abruptly turned off after a defined time interval (figure 2). Altogether, 12 different final values T_{fin} were achieved for one measuring series: T_{fin} = ±0.14 Ncm, ±0.34 Ncm, ±0.55 Ncm, ±0.88 Ncm, ±1.05 Ncm, ±1.43 Ncm. In each series, the slope $|dT/dt|$ was identical for all $T(t)$. The measuring unit was engineered as a mobile unit so that it could be used to examine patients in normal orthodontic practices.

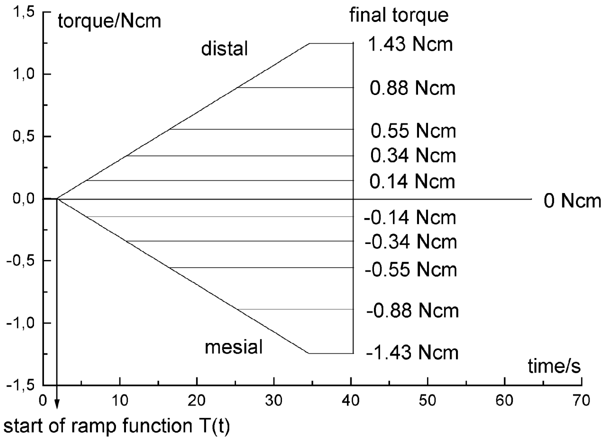


Fig. 2. Each measuring series consisted of a set of torque–time functions which were applied to a premolar. The single functions $T(t)$ started at zero with a constant magnitude of the slope, reached preset final torques T_{fin} which were then set to be constant. After a preset time period (here 41 sec), the torques were set to zero

2.2. Material

22 persons having natural spacing between their teeth were measured. Therefore neither mesial nor distal displacement of the tooth crown was hindered by contacting the adjacent teeth.

3. Results

3.1. Thresholds

In an individual measuring series (figure 3a), the respective response functions $\alpha(t)$ were delayed after application of the functions $T(t)$ as it could be expected for a viscoelastic model of the PDL. The curves $\alpha(t)$ initially overlapped as expected since always the same slope dT/dt was used to reach the defined final values T_{fin}. Apart from offset fluctuations, the rotational angle always reached constant final value α_{fin}. After turning off the motor, the tooth relaxed and returned to its initial neutral position. The corresponding angle–torque characteristic $\alpha(T)$ was provided with the final values α_{fin} and T_{fin} (figure 3b). It seemed to confirm Hooke's law. It had a sigmoid form. But it was asymmetrical in sign indicating that the rotational free

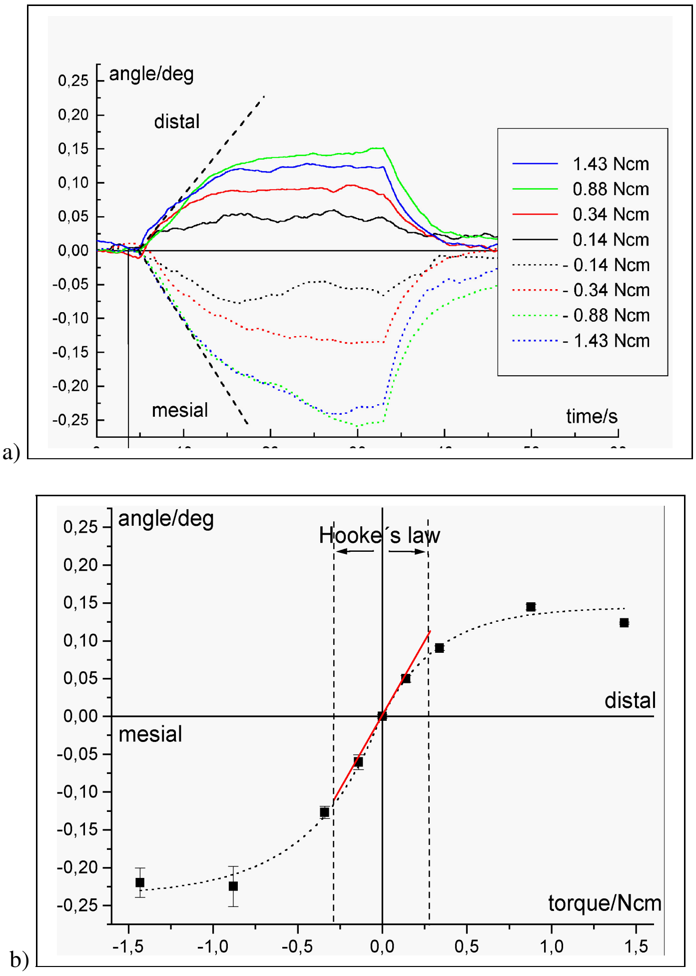


Fig. 3. Age of subjects: 14 years
Left: recorded set of angle–time curves $\alpha(t)$ corresponding to the set of $T(t)$ of figure 2.
Black dotted lines: common initial slopes of $\alpha(t)$
Right: corresponding angle–torque characteristic $\alpha(T_{\text{fin}})$.
Further details in the text

space depended on sign. In the second case, however, the torques at ±0.34 Ncm did not produce any tooth rotation (figure 4). Thresholds were reached for both signs of rotation: The torques T_{mes} (~–0.3 Ncm) and T_{dis} (~+0.3 Ncm) had to be overcome in order to make the tooth rotation possible. In most cases, similar thresholds were measured. But the absolute individual thresholds could differ in direction of rotation. Therefore the individual arithmetic mean $T_{\mathrm{mean}} = T_{\mathrm{mes}} + T_{\mathrm{dis}}$ was calculated. In the table, the variables T_{mes}, T_{dis} and T_{mean} as well as the t-test for the 22 test persons were statistically summarized.

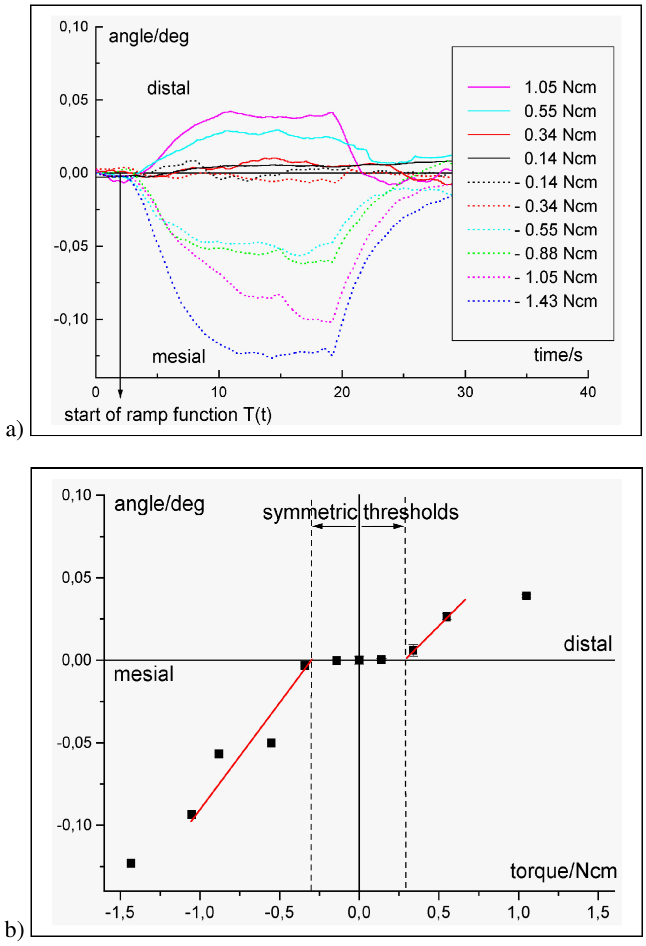


Fig. 4. Age of subjects: 10 years
Left: $\alpha(t)$-set. For small final values ($|T_{\mathrm{fin}}| = 0.34$ Ncm) the corresponding $\alpha(t)$ could not be different from zero
Right: the corresponding $\alpha(T_{\mathrm{fin}})$-characteristic.
Further details in the text

Table. Thresholds for teeth with natural spacing, $N = 22$

Variable	Mean/ Ncm	SD/Ncm	Student-test
T_{mes}	–0.178	0.170	$p < 0.0001$ +++
T_{dis}	+0.135	0.108	$p << 0.0001$ +++
T_{mean}	–0.0428	0.184	$p = 0.2878$ –

Statistically the ensemble of 22 teeth with natural spacing show highly significant thresholds for both signs of rotation. Their averages $<T_{\text{dis}}> = +0.135$ and $<T_{\text{mes}}> = -0.178$ Ncm are within orthodontic significant ranges. Since the average $<T_{\text{mean}}> = <T_{\text{mes}} + T_{\text{dis}}>$ does not differ from zero, it can be assumed that no preferred direction exists for thresholds.

3.2. Initial stiffness

Based on the characteristics $\alpha(T)$ we determined the initial stiffness $dT/d\alpha$ of the PDL directly after exceeding the respective thresholds: $dT/d\alpha = k_{\text{mes}}$ and $dT/d\alpha = k_{\text{dis}}$ corresponding to the sign of rotation. Then we calculated the asymmetry factor $A_k = (k_{\text{dis}} - k_{mes})/(k_{\text{dis}} + k_{\text{mes}})$ for each tooth. The average $<A_k> = -5.7 \cdot 10^{-3}$ (SD = 0.041) did statistically not differ from zero: the initial stiffness of the PDL was not found to depend on the sign of rotation.

3.3. Viscosity

Corresponding to the stimulus function $T(t)$, each response function $\alpha(t)$ consisted of three parts. If one assumed viscoelastic behaviour of the PDL, the function $\alpha(t)$ could be calculated. For the two-parameter model the following formulas hold:

I. For $0 \le t \le T_{\text{fin}}/a$:

$$\alpha(t) = (a/k) \cdot t - (a \cdot \eta)/k^2 \cdot [1 - \exp(-\lambda t)] .$$

II. For $T_{\text{fin}}/a \le t \le t_{\text{out}}$:

$$\alpha(t - T_{\text{fin}}/a) = (T_{\text{fin}}/k) \cdot (1 - \exp(-\lambda t + \lambda T_{\text{fin}}/a)) + \alpha(T_{\text{fin}}/a) \cdot \exp(-\lambda t + \lambda T_{\text{fin}}/a) .$$

III. For $t_{\text{out}} \le t$:

$$\alpha(t - t_{\text{out}}) = (T_{\text{fin}}/k) \cdot \exp(-\lambda t + \lambda t_{\text{out}}) \quad \text{with} \quad \lambda = k/\eta .$$

k is the stiffness and η is the viscosity parameter. We individually fitted the three parts of the measured functions $\alpha(t)$ – whose T_{fin} were in the range of constant differential stiffness $k = dT/d\alpha$ – by using η, as the only fitting parameter. 60 response functions could be taken into account. For part I the fitting made no sense because this part was too small. The fitting viscosity parameters of parts II and III differed significantly ($p << 0.0001$): η of part III was smaller than η of part II. The curves $\alpha(t)$ could not consistently by described by simple viscoelasticity.

4. Discussion

4.1. Measuring method

The reproducibility of the measurements was tested in vitro and in vivo. In vitro, the experimental error was smaller than 1%. In vivo, the reproducibility was studied in one measurement series and in two separate measurement series. The latter needed the time interval due to assembling and disassembling of measuring equipment. At the same stimulus function $T(t)$, 12 successive measurements of the curves $\alpha(t)$ carried out for about 30 min were almost identical with a tendency towards decreasing stiffness. Measuring series being repeated after four hours due to assembling and disassembling showed an experimental error of less than 10%. This precision was based on the extreme rotational resolution of 10^{-3} deg optical measuring system. For more details see [17].

4.2. Thresholds and viscosity

LEAR and MACKAY [9] applied lingually directed forces in vivo to premolars. Only when did the forces exceed a certain threshold, the loaded teeth moved towards the tongue. However, Lear and Mackay used a very short time-frame for measuring, so that their thresholds could be explained, considering viscoelasticity, simply by the delay as the tooth needed some time to respond. The measurements substantiated that the PDL must not be modelled by a viscoelastic layer consisting of a simple polymer. There are 3 reasons for taking shear thinning into account: i) The response functions $\alpha(t)$ could not be described by a constant viscosity parameter. ii) The cases presented in figure 4 suggested high viscosity under small external loads. iii) The statistical independence of the thresholds in sign (table) confirmed this point of view. On the other hand, we found large interindividual variances in the thresholds T_{dis} and T_{mes} and in their arithmetic mean $T_{\mathrm{dis}} + T_{\mathrm{mes}}$ which were not produced by the unreliability of measurement. Hence the shear thinning properties of the PDL seem to differ interindividually on a large scale, and further mechanism like pretensions in the gingival apparatus seem to be involved [18]–[20].

5. Outlook

Altogether the measuring method presented provides a sensitive tool to check the biomechanical status of the PDL of a tooth. In order to substantiate its clinical value and use, systematic and extensive studies have to be carried out in the future. Since the equipment can be used in normal orthodontic practices this work can be done without further ceremony.

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