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Measurement of tooth and implant mobility under physiological loading conditions

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SUMMARY

In vivo measurement of the mobility of teeth under physiological loading has been subject of research for years. Comparing the deflection under load of dental implants with teeth provides valuable input for designing restorations spanning both teeth and implants. Physiological force rise time of about 50–100 ms and displacement of 10–100 μm requires high spatial and temporal resolution of the measurement set-up. Using an optical system attached to the teeth/implants to be measured and a light source attached to a point of reference, displacement of teeth and implants under axial and lateral loading was measured on a series of volunteers. Axial displacement of teeth shows strong time dependence consistent with (hydraulic) damping not observed for lateral loads. Displacement under lateral loading was found to be about one order of magnitude higher than under axial load. For dental implants elastic deflection was observed in axial and lateral direction without measurable influence of the load rise time. For purely axial loading, dental implants and teeth show similar deflection under physiological force rise time but for lateral loading the considerably difference between teeth and implant may put some restrictions on the construction of tooth–implant-bridges, especially for teeth in the anterior region.

1. Introduction

Understanding kinetics of teeth and implants under physiological loading are of fundamental importance in dentistry, especially when it comes to design and construction of tooth–implant bridges: fixed partial dentures supported by teeth on one side and implants on the other. The classical model of tooth kinetics studies derived by earlier work (Mühlemann, 1967; Mühlemann and Rateitschak, 1965; Parfitt, 1960) suggest that for tooth–implant-bridges the more rigid part (i.e. the implant) could be overloaded and generally a higher rate of failure should be expected for such restorations. However, clinical experience has shown that tooth–implant bridges are not subject to extraordinarily high failure rates, leading to the assumption that the periodontal ligament's dynamic properties have not been fully understood and the existing models do not sufficiently represent real teeth.

The biomechanical models which have been derived to explain these properties commonly describe a combination of an elastic (coil spring) and a viscous component (damper) (Lukas et al., 1992; Schmitt, 2000; Sanctuary et al., 1985). Static measurement methods, as described by Niedermeier (1984), measure the deflection of a tooth as it reacts to a defined force. Methods of dynamic measurement (Hoedt et al., 1985; König et al., 1981; Körber, 1970) record the recovery kinetics of the periodontal ligament in reaction to temporally variable force loading. Known limitations of these methods are the characteristics of the applied forces, which, particularly in case of the static measurements, do not resemble the impulsive loading during mastication. Research conducted earlier by Richter (1998, 1995) had focused on the transmission of forces into teeth. It was shown that during mastication loading, forces rise at rates of up to 250 N/s with an absolute force maximum on the order of 50 N, achieved within 20 ms (Fig. 1). These are the critical parameters that must be met by a measurement setup in order to reproduce the physiological conditions. The existing measurement methods are not suited to gain understanding of the dynamic response of teeth to such loading. A further difficulty is presented in finding a reference- or zero-point to the object in motion (Eckhardt, 1982). Also, the setup of the aforementioned methods often influences the teeth's kinetics. Improvements on these setups come with new immobile travel sensors and have been put to use by Lukas et al. (1977). Another variant of dynamic recording relies on inertia of the system comprising tooth and periodontal ligament (Niedermeier, 1984; Schulte et al., 1983), enabling free-hand testing without referencing, but this setup achieves only fractions of the force levels which occur under physiological loading.

The described difficulties and limitations of the methods employed to measure tooth mobility demonstrate that, so far, it

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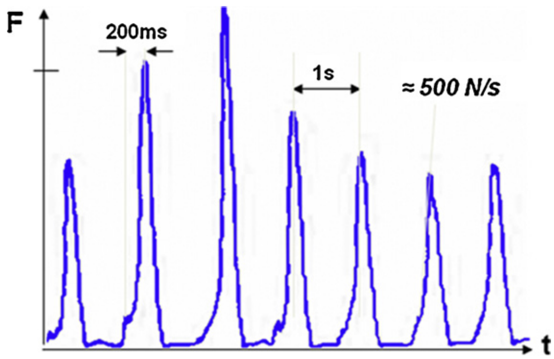

Fig. 1. Typical force levels of physiological masticatory action measured in situ. The force is built up within 200 ms, in which an average force level of 50 N is achieved. The resulting force rise time of 250 N/s served as a benchmark for this study.

has not been possible to sufficiently assess the kinetics involved. A methodology which allows for measurement with definitive referencing as well as reproducible and realistic introduction of dynamic forces is therefore desirable. It was the purpose of this study to establish a measurement method allowing for assessment of dental kinetics under loading as it occurs under dynamic physiological masticatory action. A contact-free optical measurement setup was developed to give 3 dimensional and temporal results at high resolution.

2. Materials and methods

In order to eliminate mechanical interferences, a 2 component optical system was designed. A small 650 nm LED was attached to the tooth to be measured. The emitted light was focused through a micro lens onto a CCD camera which could be mounted to a reference object, typically a tooth or an implant-supported crown within the oral cavity not affected by the loading forces. This captured blob of light, as it was projected on the chip, could be interpreted in terms of motion of the reference object in 3 dimensions: axial motion is depicted as movement of the light body along the *Y* axis and vestibular-oral motion along the *X*-axis. Information regarding the mesio-distal motion can be extracted from the blob's change of diameter as it moves in and out of focus. The micro camera (J. Neumann, Fürth, Germany) contains a custom CCD chip which is capable of capturing a 392 × 292 pixel picture at a maximum of 100 frames per second (resulting in a resolution of 10 ms). The analog signal was fed into an in-line preamplifier and digitized by a Matrox Meteor II frame grabber card (Matrox Imaging, Dorval, Quebec, Canada). For calibration the LED and camera were mounted in a rig consisting of 3 μm stages and a custom frame. In this frame the blob was centered on the screen and set such that the diameter was of medium size. LED and camera were fixed together and to a temporary carrier with adhesive wax before being removed from the rig and inserted into the subjects' mouths (Fig. 2).

All teeth, whether they served as reference or object of interest, were clinically examined for signs of periodontal disease (increased mobility, loss of attachment or bleeding on probing). Teeth or implants without interproximal contacts were chosen as reference points. The tooth to be measured was force loaded using a VersaTest AFG 2500 (Mecmesin, Santa Rosa, USA) which was linked via RS232 to a control-PC where the applied force levels over time were recorded. Custom tips were used which suited the anatomy of the tooth best. Measurements were carried out on 5 informed and consenting volunteers. In total, 10 teeth and 4 implants were measured in 5 test persons under lateral and axial loading. Axial forces ranged up to 80 N while the lateral forces were kept below 30 N (applied to the incisal edge) in order to avoid damage to the tooth. LED and camera were bonded with ProTemp 3 Garant (3M Espe, Neuss, Germany) to the teeth without any conditioning. After the measurement the components and residual composite could be carefully removed with a scaler.

The acquired video data was exported into an avi file, which in turn was then imported into custom software for post-processing and statistical analysis. Since correct analysis could be influenced by dimensional distortions caused by lens errors of the optical setup, a calibration was carried out immediately after manufacturing. Although it was found that the Z-shift did indeed have an influence on the scales of the *X* and *Y* axes, the effect was less than 10%. The statistical analysis had to deal with several obstacles: since the light blob was not perfectly circular or elliptical, and, as it moves in the *X* and *Y* direction, parts of it leave the screen. To address these issues, mathematical methods were used so that the acquired data could be analyzed in a subsequent step. First, the blob is turned into an ellipse by an idealization of the object's circumference. This is achieved in a four step process:

– By a predefined threshold, the blob is binarized.
– The number of "white" pixels per horizontal and vertical line are counted and compiled in 2 histograms.
– All lines with a value of 33.3% and smaller are then ignored, and the mean value from the "gated" histogram is assumed as the new center point's location on the respective axis.
– From the distance of the center point line to the histogram boundaries with zero-values, an ellipse is calculated.

Secondly, it was necessary to find a method of completing the ellipse when parts of it were outside of the screen's boundaries. Ordinarily, an ellipse's area can be calculated, provided the principle axes and the center are known. With part of the ellipse outside of the capture, however, these parameters vary. Accordingly, a proprietary method was derived to complete the body based on the remnants and of the ellipse, from which the center point can be deduced. Motion of the calculated center point is graphically depicted in a graph which displays the ellipse's center point's motion in 3 dimensions over time (GnuPlot, public domain). After synchronization of the timeline of the 2 different measurement sets, displacement could be plotted against loading force.

3. Results

All measurements were well tolerated by the volunteers. Axial and lateral displacement of teeth and implants with different force levels and force rise times were measured. Axial displacement of teeth was found to have a strong dependency on the force rise time, as opposed to that observed on implants. The relationship between axial displacement and rise time is depicted in Fig. 3 for a force level of 30 N showing an almost exponential drop of the axial displacement with faster rise times. By contrast, implants showed no variation of displacement over force rise time under axial or lateral loading. Here, motion was found to be linear with increasing load.

The lateral motion in reaction to a lateral force of a tooth and an implant are shown in Fig. 4. The lateral motion was found to be largely independent of the force's rise time, and was comparatively large even at low force levels, e.g. 120 μm at a maximum excitation of 10 N after either 50 ms or 1 s, which can be as high as 10 times as much as that observed when loading implants with laterally acting forces. Accordingly, implants exhibit the same linearity between force level and movement as under axial loading.

With increasing force rise times it was observed that, under physiological conditions (i.e. with force rise times of about 0.1 s) the displacement of teeth versus that of implants were on the same