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The stress state of the fraenal notch region in complete upper dentures

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ABSTRACT

The present study determines the stress field in the region of the labial flange of the complete upper denture (CUD).

Using commercial edentulous molds and standardized procedures eight identical CUDs were fabricated with an initial fraenal notch of 5 mm. Three addition notch conditions were produced by deepening the notch two times giving a total depth of the notch of 7 and 9 mm respectively. Finally an incisal diastema of 7 mm was created in every CUD.

Three elements rosette strain gauge was cemented onto the midline of each denture specimen near the fraenal notch, for calculating the two principal stresses and the maximum shear stress.

It is less possible that a failure crack in a CUD will be initiated from the region of the fraenal notch, due to the compressive nature of the principal stresses (they are varied significantly among the four notch conditions with $P = 0.035$ for σ_1 and $P = 0.007$ for σ_2) and the low value of the maximum shear stress. The creation of an incisal diastema significantly decreased the values of the principal stresses σ_1 ($P = 0.012$) and σ_2 ($P = 0.025$). Further investigation is needed to detect the region of the CUD where a failure crack may be initiated.

1. Introduction

The deformation of complete upper dentures (CUDs) remains a complicated research problem. Furthermore the deformation of the palatal region of the CUD is of great importance and should be considered in conjunction with the deformation of its other regions, since the acrylic denture plate, under loading deforms uniformly.

The stresses and strains in the palatal region of the CUDs have been measured experimentally using several methodologies, including brittle coatings [1], strain gauges [2–9], photoelastic models [10,11], holography [12], a scanning electron microscope replica technique [13], and simulations such as finite element analysis (FEA) [14]. The above researches referred to the maximum values of strains and stresses under a single load (maximum load), without taking into account the realities of mastication which takes place under fluctuated loading. Another important issue not addressed by these studies, concerns the direction of the stresses and whether it is constant or varies. Three recent studies using rosette strain gauges under simulated mastication conditions (alternated load), showed that the complexity of applied loads during normal functioning both in terms of their magnitude and direction, in combination with alterations in the directions and magnitudes of the principal stresses in the posterior field of the palatal segment induces a complex multiaxial stress state in the palatal segment of CUDs, leading to multiaxial fatigue [15–17].

Furthermore, there is a view that many CUD fractures result of the presence of a large fraenal notch or midline (incisal) diastema, since it is well known that these features predispose to eventual fracture by stress concentration [1,3,5,13].

FEA of the anterior segment of a maxillary complete denture has revealed the substantial stress-concentrating effect of a labial (fraenal) notch in a CUD. When a median (incisal) diastema is superimposed on this, the stress at the notch tip is increased by at least 25%. As the diastema increases in width, the stress levels tend to diminish, but remain above the strength of some of the commercially available denture-base resins. The results of that study indicate that as the width of the diastema increases, the stress concentration decreases [18].

A three-dimensional FEA method was used to analyze the stress and displacement of maxillary complete dentures and their underlying supporting tissues under a vertical occlusal force in centric occlusion [19]. The results showed that the tension stresses within the denture base were distributed mainly on the top of the alveolar crests and back border, while the compressive stresses were distributed mainly on the central section of the palate and labial flanges.

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The brittle materials that are normally used to fabricate dentures, such as polymethylmethacrylate (PMMA), exhibit greater compression strength (150 MPa) than tensile strength (80.4 MPa) and shear strength (122 MPa) [20]. Furthermore, brittle materials such as denture resin are sensitive to the presence of surface notches. It is therefore very important to establish the type (tensile or compressive) and magnitude of the maximum surface stresses, as well as their orientation [20].

It is well known that there are three possible modes of crack initiation and propagation in a CUD (as in every mechanical structure): the crack-opening mode, which is due to tensile loads, and the shearing and tearing modes, which are due to in-plane and out-of-plane shear loads, respectively [21]. This makes it necessary to calculate the principal stresses and maximum shear stress, as well as their orientations, in order to determine the stress field of the loaded structure.

To assess the contribution of labial notch in the failure of the CUD, the fatigue property of PMMA during repeated loading, should be also reviewed. An effort has been made to evaluate static and dynamic flexure properties of a variety of acrylic resins. It was shown that the visible light-polymerized urethane dimethacrylate resin (Eclipse) showed greater flexure strength than all PMMA heat-polymerized resins, for both static and cycled groups ($P < 0.001$). The heat polymerized PMMA material did not significantly differ from each other after static or cyclic testing [22]. In a similar study a comparison of the fatigue resistance between composite resin and ceramic posterior occlusal veneers has been made. All specimens were loaded for a maximum of 185,000 cycles. The IPS Empress CAD failed at an average load of 900 N, with no specimen withstand all 185,000 load cycles (survival 0%), while IPS e.max CAD and Paradigm MZ 100 demonstrated survival rates of 30% and 100% respectively [23].

There is considerable disagreement about the contribution of the fraenal notch to the failure of CUDs. Strain gauges could be considered as a reliable method for determining the complete state of surface stresses.

The purpose of the present research was to determine the complete stress state near the fraenal notch of the labial flange in CUDs during loading and to compare this stress field to the corresponding field of the palatal area of the dentures. To this end, the principal stresses, the maximum shear stress, and their orientations near the fraenal notch were measured. Furthermore, whether increases in the depth of the notch along with the presence of an incisal diastema could affect the stress state of the fraenal notch area was determined. The question as to whether the existence of the fraenal notch may be the cause of failure of the CUD during service was also considered.

2. Materials and methods

2.1. Specimens preparation

Eight identical CUDs were constructed according to a previously applied methodology which is briefly described in the followings [15–17,24].

Two commercial molds of edentulous jaws were used: one of the upper and one of the lower jaw (Edentulous molds, size 55; Columbia Dentoform, Long Island, New York, USA) [15–17].

These molds were used to fabricate two prototype casts from type III dental stone (Hydrock, KerrLab, Orange, California, USA). Using standardized methodology, two wax denture bases of uniform thickness (3 mm) were constructed using wax denture sheets (Tenatex, Associated Dental Products, Wiltshire, UK). Guidelines were drawn on the rims to indicate the position of the crest of the ridges, and waxed rims were placed so that their long axes coincided with the crest of the residual ridges. The anterior teeth (Upper Anterior, Uhler Dental Supply, Chicago, Illinois, USA) were arranged according to standard procedures [15–17,24]. The posterior teeth (Upper Posterior, 33°; Uhler Dental Supply) were placed with the central grooves of their occlusal surfaces coinciding with the guidelines. Their occlusal surfaces were arranged according to standard procedures in order to reproduce the curves of the anteroposterior and lateral compensating curves [24]. The corresponding wax complete lower denture (CLD) was then constructed in the standardized vertical dimensions of occlusion, using the corresponding lower teeth (Lower Posterior, 33°; Uhler Dental Supply).

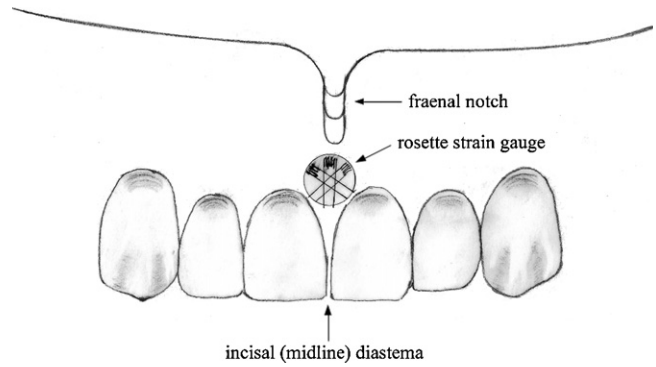

Fig. 1. A frontal view of the labial flange of the CUD. The four conditions of notches are distinguished as well as the position of the rosette strain gauge.

Finally, two waxed dentures were constructed in normal occlusion using methods, materials, and standardized procedures that have been described elsewhere [15–17]. The waxed CUD was removed from the upper cast of the articulator and used to construct a two-piece mold to reproduce eight identical standardized CUDs. A new cast was placed in its respective position in the lower half of the mold (made from Plexiglas), while the upper half (made with silicone) was fixed in its position on the lower half. Finally, molten base-plate wax (Tenatex, Associated Dental Products) was poured into the intervening space. This procedure yielded eight fully waxed CUDs and a waxed CLD, which were then flasked using an acrylic-resin material in accordance with the manufacturer's instructions (Paladon 65, Heraeus Kulzer, Hanau, Germany). The above procedure resulted in eight identical CUDs with teeth made from the same material used to construct the denture bases. The acrylic dentures were finished according to standard finishing procedures for acrylic-resin denture bases [24]. During grinding and polishing of the definitive acrylic-resin dentures, the thickness was measured at six points on both the labial and buccal flanges with an analog thickness gauge with 0.1 mm precision (K series, Schmidt Control Instruments, Waldkraiburg, Germany) to ensure that the bases of all of the denture specimens had the same thickness (3.0 ± 0.1 mm) [16,17].

2.2. Strain gauge

One rosette strain gauge (type KFG 5-350-D 17, Kyowa Electronic Instruments, Tokyo, Japan) with three strain elements was cemented onto each identical upper denture with cyanoacrylate adhesive (type CC-15A, Kyowa Electronic Instruments). The rosette strain gauge was cemented to the outer surface of the labial flange and the midline of the dentures such that the center of the rosette was positioned at a point 9 mm from the deepest point of the initial fraenal notch, while the axis of the middle element coincided with the midline axis of the denture. The right element of the rosette coincided with axis x oriented 45° clockwise from the midline, while the left element coincided with axis y oriented 45° counterclockwise (Fig. 1).

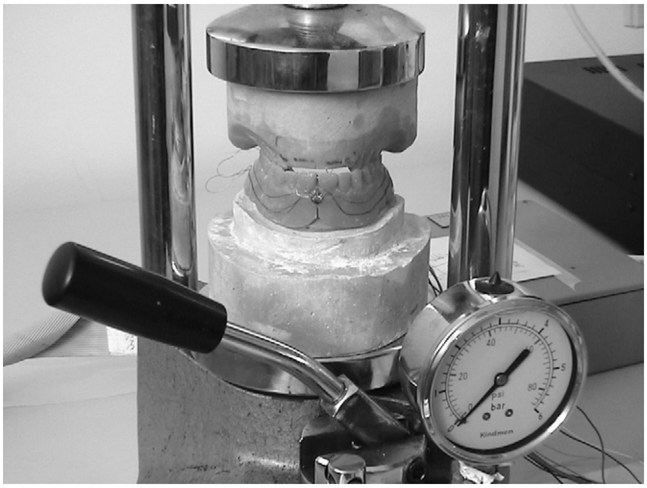

Fig. 2. The two dentures (upper and lower) on their casts, mounted between the plates of the press.

2.3. Specimens loading

Each upper-denture specimen and the selected lower denture were mounted on die stone casts, using the methodology of previous studies, in order for the results to be comparable with these studies [15–17]. These casts were produced by pouring high-strength type IV dental stone (Vel-Mix, KerrLab) into the two commercial molds. Before the denture specimens were placed on the load casts, the intaglio surfaces were painted with medium-viscosity silicone (Coltoflax, Coltene/Whaledent, NJ, USA) to simulate the oral mucosa. To ensure that the thickness of the silicone was similar to the average thickness of the masticatory mucosa in vivo, 2-mm and 1.5-mm thicknesses of die stone were removed from the residual ridges of the maxillary cast and the mandibular cast, respectively, before the placement of the painted specimens [15–17].

The upper and lower dentures were positioned in centric occlusion, and their mounted casts were placed between the plates of a hydraulic press (Bego Hydraulic, BEGO, Bremen, Germany) (Fig. 2).

Each denture specimen was loaded four times, in four different labial notch conditions: (1) with the initial notch (5 mm in depth), (2) after deepening the notch by 2 mm (to a total notch length of 7 mm) using a cutting wheel (Ceraflex high-cutting-efficiency wheel, Bredent, Germany), (3) after deepening the notch by a further 2 mm (to a total notch length of 9 mm), and (4) after creating an incisal (median) diastema by making a 7 mm slot between the two central incisors. These loadings were applied at time intervals of 1 h to allow the acrylic base to recover from the previous loading each time [25].

Given that complete dentures are subjected to varying loads in vivo and for simulating the real mastication process, the denture specimens were loaded in five loading steps: 20, 40, 60, 80, and 100 N. These loading steps were selected as representative loads of mastication function. During this function these loads are fluctuated between a minimum and a maximum load. The maximum load of 100 N is consistent with a previous study showing that the force exerted by edentulous patients at the vertical dimension of occlusion ranges from 30 to 110 N [26]. The increases in loading (speed of loading) were made with a rate of 20 N/14 s.

2.4. Strain measurement

Three associated strains (namely ε_A, ε_B, and ε_C) were measured at each rosette strain gauge and were then substituted into standard equations in order to determine the two principal strains, ε_1 and ε_2, principal stresses σ_1 and σ_2, and the angle Φ formed between the stress with the larger magnitude and the *x*-axis, as defined previously [15–17,21]. A positive value of Φ would indicate that the larger stress was counterclockwise (to the left) of the *x*-axis, whereas a negative value would indicate that it was clockwise (to the right) of this axis.

Two principal stresses are present in a plane state of stress, namely σ_1 (maximum algebraic value) and σ_2 (minimum algebraic value) acting on planes named the principal planes. In the plane state of stress, the two principal stresses are always mutually perpendicular; that is, σ_1 and σ_2 are separated by an angle of 90°. Shear stresses vanish on these principal planes. The maximal shear stress (τ_{max}) occurs on a plane that is 45° to the principal planes, with a value given by the following equation [15–17,21]:

$$\tau_{max} = \frac{\sigma_1 - \sigma_2}{2}$$

Following standard convention in stress analysis, a positive principal stress was designated as tensile and a negative principal stress was designated as compressive (note that the sign convention used for shear stress is normally not important) [21].

The mean value of each stress (σ_1, σ_2, and τ_{max}) and of angle Φ was calculated from the five measured stress magnitudes (i.e., in response to the five loading steps). These mean values were determined for every denture specimen and for the four notch conditions. The final mean value of the stress was determined from the eight stress values (i.e., from the eight identical complete-denture specimens), and was considered the representative value of the stress for the corresponding notch condition.

2.5. Statistical analysis

Due to the low number of specimens (eight), nonparametric tests were applied for statistical analysis, using standard statistical software (SPSS version 15.0 for Windows, SPSS, Chicago, Illinois, USA). The Kruskal–Wallis test was used to assess variations of the means among the four notch conditions. The Wilcoxon test was used to determine the significance of differences in the stress magnitudes between all possible pairs of notch conditions, with a probability cut off of $P = 0.05$.

3. Results

In Fig. 3 a graphical representation of the level of the stresses in the four notch conditions is presented, including the statistical differences. Figs. 4 and 5 show the curves of strains vs. time during loading and their resultant stresses vs. time respectively, concerning the initial notch condition for the specimen No 7 as a representative specimen among the eight specimens.

3.1. Maximum principal stresses

The two principal stresses, σ_1 and σ_2, were recorded for all of the denture specimens (eight CUDs), and they were both found to be compressive. Increases in loading led to increases in the principal stresses, but did not change their signs. These two stresses varied significantly among the four notch conditions ($P = 0.035$ and $P = 0.007$ for principal stress σ_1 and σ_2 respectively).

Deepening the fraenal notch did not change the compressive nature of the principal stresses. The creation of an incisal diastema decreased the values of the principal stresses for a fraenal notch depth of 9 mm to a statistically significant level for both principal stresses σ_1 ($P = 0.012$) and σ_2 ($P = 0.025$).

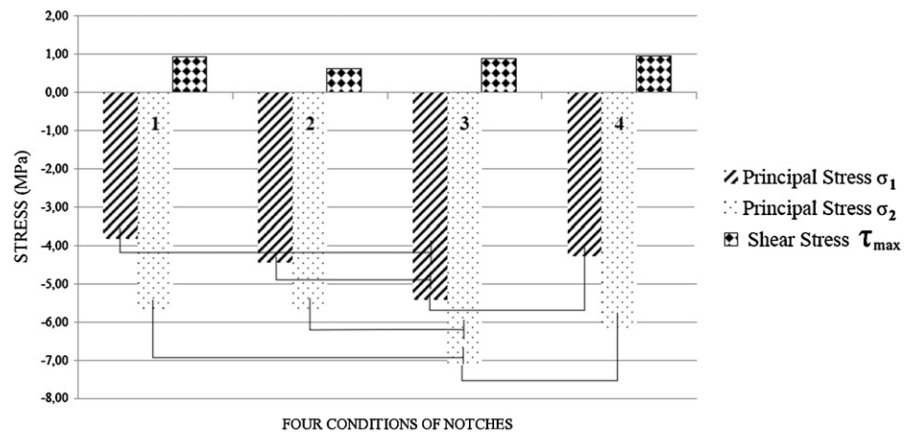

Fig. 3. The mean values of the principal stresses and the maximum shear stress in the four conditions of notches: 1 – the initial notch of 5 mm, 2 – the deepening of the notch at 7 mm, 3 – the deepening of the notch at 9 mm and 4 – the creation of an incisal diastema. The horizontal lines connect magnitudes which are statistically different ($P < 0.05$).

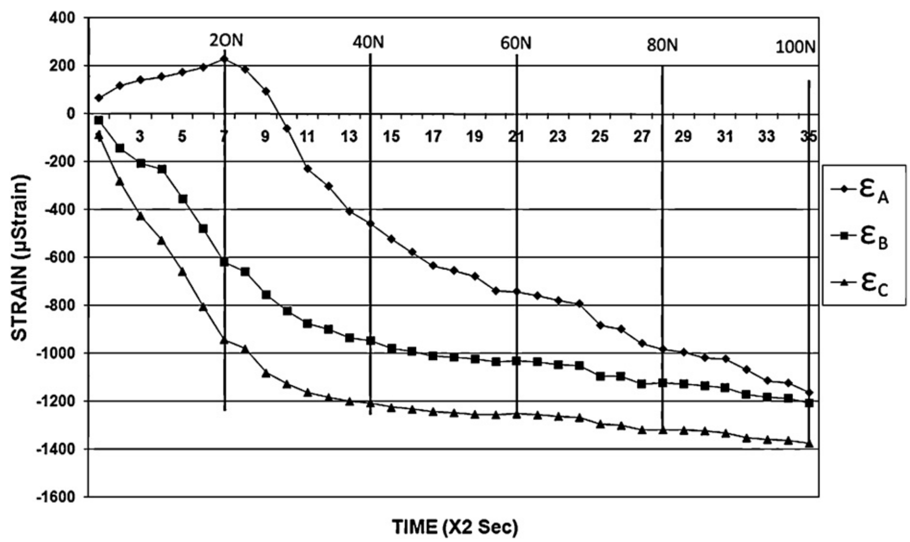

Fig. 4. The recordings of strains relating to the initial notch condition, on the labial flange of specimen No 7, as a representative specimen. The vertical lines correspond to the times during which the load reached the indicated values.

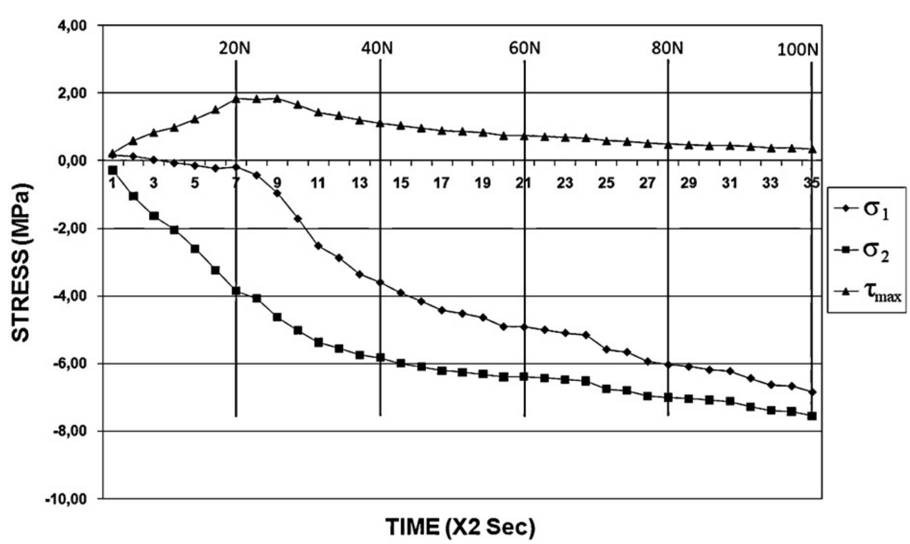

Fig. 5. The calculated stresses relating to the initial notch condition, on the labial flange of specimen No 7. The vertical lines correspond to the times during which the load reached the indicated values.

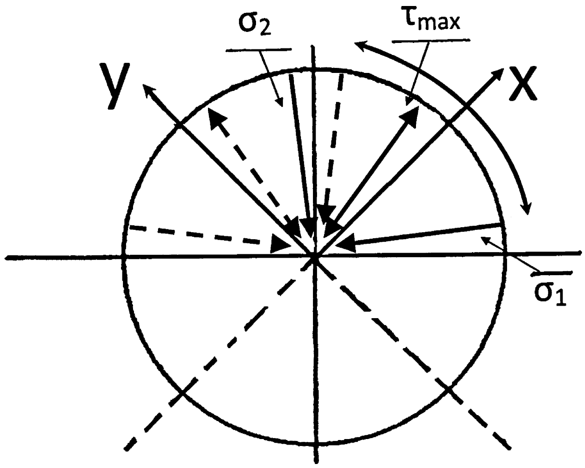

Fig. 6. A graphical representation of the stress field on the labial flange of the CUD.

3.2. Maximum shear stress

Given that the two principal stresses were both found to be compressive, the maximum shear stress τ_{max} was extremely low in all four notch conditions. The mean maximum shear stress (τ_{max}) did not vary among the four conditions (P = 0.120). In other words, the maximum shear stress was practically stable during loading in all four notch conditions. The creation of an incisal diastema did not change the maximum shear stress (P = 0.170).

3.3. Orientation of the stresses

The stress field of the area near the deepest point of fraenal notch exhibited some degree of instability in all four notch conditions, in terms of both the sign and magnitude of angle Φ. During loading, the mean value of angle Φ was found to change from -37.2° to $+34.7^\circ$.

This variation indicates that the directions of the principal normal stresses and of the maximum shear stress fluctuated with the load in the region of the labial flange.

A schematic representation of the stress field of the region of the fraenal notch is shown in Fig. 6. In this figure, the arrows pointing inward denote the directions of the compressive principal stresses, whereas the double-ended arrow denotes the direction of the maximum shear stress. The double curved arrow denotes areas where the two principal stresses and the maximum shear stress occur during variations in the loading or, in other words, the range of variation in angle Φ.

4. Discussion

The complexity of applied loads during normal functioning, in terms of both their magnitude and direction, in combination with alterations in the directions of principal stresses and in their magnitudes, induces a complex multiaxial stress state in the stress field of the labial flange of the CUD [15–17]. It is well known that the maximum compressive stress has a beneficial effect on the fatigue life of most mechanical structures, and that crack initiation and other properties are directly related to both tensile and shear stresses, depending upon the three possible modes of fracture. The logical consequence of these assumptions is that in the stress field of the labial flange of the CUD, where two compressive principal stresses and a very low shear stress were recorded, it is less likely that a crack or failure will be initiated. Fluctuation of the directions of the compressive stresses, as well as their increasing value with increasing loads, characterizes a multiaxial stress state. For this reason, it cannot be argued that it is impossible for a crack of fracture to be initiated from this location of the CUD.

Strain gauges provide a simple and accurate method for measuring the surface stresses that develop on the plane state of stress. The application of this method in vitro can provide data that are more useful than that yielded from in vivo measurements, since inadequate sealing of gauges may produce short circuits that could introduce measurement errors [16,17].

The use of two- and three-dimensional photoelastic models has limited application in investigations of complete dentures due to the difficulty of preparing thin photoelastic sections (sheets) for denture models that will exhibit distinct fringes [16,17].

FEA techniques have recently been introduced into the analysis of the deformation of complete dentures [14,18,19]. An FEA solution is only approximate due to the use of discrete mesh models, which are seldom exact representations of the physical problem, although the errors can be reduced by using a sufficiently fine mesh [16,17]. Moreover, it seems that when using FEA, it is difficult to determine the entire stress field, namely to compute the values and the directions of principal stresses under the conditions of fluctuating loading. Perhaps these limitations are responsible for the discrepancies in FEA research results concerning the influences of fraenal notches and incisal diastemas on the failure of CUDs. Some researchers using FEA argue that the presence of a large fraenal notch can give rise to a stress level that is likely to induce crack formation, while others using the same method suggest that denture failure is unlikely to occur at a shallow fraenal notch [18,19].

Whilst FEA methods are unable to calculate the complete state of stress, the results of the present study are consistent with recent FEA research suggesting that a single load of 230 N (perhaps too high for an edentulous patient) induces only compressive strains in the labial flange of the CUD [19]. However, that study only measured the strains (i.e., without computing the resultant stresses), and only on the three basic axes. The results of the present research demonstrating that the stresses in the region of the fraenal notch are reduced with the creation of an incisal diastema are also in agreement with another FEA study that found that stress levels tended to diminish with increasing diastema width [18].

The use of strain gauges may be valuable for evaluating the surface stresses in complete dentures, which is crucial for the strength of brittle materials such as PMMA.

The greater strength of PMMA in compression than in tension and shear suggests that regions of an acrylic-resin base subjected to compressive stresses will be less prone to failure than regions under tensile stresses. Thus, the present finding that the stress field of the labial flange of a CUD is characterized by two compressive principal stresses and a low shear stress leads to the suggestion that it is less possible that a failure crack will initiate from this region, due to the following two reasons:

1. Although the direction of the principal stresses changes during loading, their magnitude remains low compared to those in other regions of the CUD such as the anterior palatal stress field [15–17].
2. Even in cases where the two compressive principal stresses reach high values, the resulting maximum shear stress would be low, and in any case lower than the shear strength of PMMA.

Notwithstanding this reasoning, further research is necessary into detecting the site of crack initiation in a CUD subjected to fatigue. Through the fatigue studies, which approach the functional loading of the CUD, it would be possible to identifying if the crack initiates in the palatal region instead of the fraenal notch of the denture [22,23].

The viscoelasticity of mucosa of the edentulous ridges and its nonuniform thickness, the absence of an exact axis of symmetry, the fluctuation in loading, the nonuniform distribution of loads, and the fluctuating cross-section of the CUD are reasons why fracture of such prostheses is a complex and still-unresolved problem for the clinician [15–17]. Thus, the strain gauges used in the present study, which simulate the aforementioned conditions, could be considered reliable tools for determining the complete stress state of the labial flange of the CUD.

5. Conclusions

Within the limitations of this study the following conclusions can be drawn:

1. The method utilizing three element strain gauges is a reliable one for determining the complete state of surface stresses in any region of the labial flange of the CUD.
2. The labial flange of the CUD near the region of the fraenal notch is under a multiaxial state of stress because increasing loads increase the principal stresses and induce fluctuations in their orientations.
3. It is less likely that a failure crack in a CUD will be initiated from the region of the fraenal notch, due to the compressive nature of the principal stresses and the low value of the maximum shear stress.
4. Deepening the fraenal notch along with the creation of an incisal diastema, did not change neither the compressive nature of the principal stresses nor the maximum shear stress.
5. Further investigation must be conducted to detect the region of the CUD where a failure crack may be initiated.

Conflict of interest statement

This is to declare that there is not any financial and personal relationship of the authors with other people or organisations that could inappropriately influence their work.

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