Strain Mapping in Teeth with Different Quantities and Qualities of Remaining Structure

Objectives: The purpose of this *in vitro* study was to evaluate strain in teeth with differing tooth surface loss utilising: The surface displacement field measured using Digital Image Correlation (DIC), and Strain Gauges (SG).

Method: 80 MOD preparations were carried out in human maxillary premolas. 10 sound premolars served as control (Control). Samples were divided into 2 groups (n=40) according to the composition of the prepared walls, composed of either enamel and dentine (E+De) or dentine only (De). Each group was then divided into 4 subgroups (n=10) according to the selected cusp height to width ratio (H:W), (A=2:1mm, B=3:1mm, C=3:1.5mm, D=4.5:1.5mm). The samples were uniaxially loaded to 130N where strain was recorded with (DIC) and (SG).

Results: With SG testing, Control samples recorded the lowest strain values and were significantly different from all test groups. However, DIC failed to detect strain in Control samples as it was too low. With DIC, group D showed the lowest strain readings among all dimension groups with significant difference from groups A and B. However, the composition of the remaining tooth structure did not show any significant effects. While with strain gauge testing, remaining wall dimension and composition had a significant effect. Group A scored the highest strain at all compositions. E+De had better resistance to load stresses than De only.

Conclusions: For both testing methodologies, height (≥3mm) and width (1-1.5mm) of the remaining tooth structure had an effect on strain. Tooth compositions of (E+De) resisted strain better than (De) counterparts at all dimensions.

Title:

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Conclusions: For both testing methodologies, height (≥3mm) and width (1-1.5mm) of the remaining tooth structure had an effect on strain. Tooth compositions of (E+De) resisted strain better than (De) counterparts at all dimensions.

Clinical Significance:

Deformation of teeth under occlusal load is particularly important to the broken-down tooth. Under loading, stresses concentrate within the remaining tooth structure. Increased loss of tooth structure can affect stress distribution within the tooth, therefore increasing the potential of tooth fracture and the risk of restorative failure or further loss.

Introduction:

Tooth fracture is a frequent restorative problem. A tooth's ability to resist fracture may be the result of a combination of clinical factors, including quality, quantity and age of remaining tooth structure [1], cavity preparation, choice of restorative material [2, 1] and tooth loading. Caries, erosion, attrition and trauma commonly remove tooth structure that in turn decreases the fracture resistance of the tooth and affect stress distribution within the tooth. Stresses within tooth structure in combination with strength properties are important to fracture resistance [3, 4].

The generation of stresses within teeth is complicated by the non-homogeneous nature of tooth structure and the irregularity of its contours. Tooth structure is composed of different materials with widely varying properties including enamel, dentine, pulp, cementum and supporting tissues of periodontium, and bone. This complex structure is subject to large variations in both the magnitude and direction of chewing forces [5].

Load application to an object causes stress concentration and structural strain. The ultrastructural integrity of the body is not greatly affected when this occurs within the elastic limit. However, stress concentration beyond this limit may result in crack formation and propagation which will eventually cause fracture and structural failure [6].

As the fracture resistance of restored teeth is lower than sound teeth, the dental practitioner is challenged by the design of the cavity preparation [7-9]. One study showed that 92% of fractured teeth had previously undergone restoration [10].

The presence of wide and/or deep restorations may be considered the highest risk to tooth fracture [11], and cavity preparation typically exaggerates the height of the remaining cusps rendering them unsupported. When unsupported cusps are loaded they may deflect, rotate or fracture [12, 9, 1]. Where fracture does not occur, the tooth-restoration interface may open as a result in deflection or torsion of a weakened cusp. This may subsequently result in marginal leakage, secondary caries formation, and possibly tooth fracture [13, 8].

Posterior teeth anatomy, with cusps and fossae, predisposes them to deflection of cusps under stress [14], whilst the form and height of the cusps influence the direction of stress.
To reduce tooth fracture, it appears to be important to maintain the marginal ridge integrity [15-18]. In intact teeth, strength is gained from marginal ridges forming a continuous band of tooth structure.

Bassir MM, Labibzadeh A and Mollaverdi F [3] showed that the fracture resistance of sound teeth was significantly reduced with Mesio-Occlusal (MO) and Mesio-Occluso-Distal (MOD) cavity preparations. When non-destructive occlusal loading was applied, Pereira et al. [9] observed that MOD cavities presented significantly higher values of strain than MO, Occlusal (O), or intact teeth.

In order to assess the remaining tooth structure, both remaining wall width and height should be examined. In the literature, few studies have assessed the amount of residual tooth structure in vital teeth. Residual dentine thickness in vital posterior teeth after all-ceramic crown preparation has been reported. The mean residual dentine thickness between the axial wall and pulp chamber in posterior teeth varied between 0.47 and 0.7mm [19]. Another study by Seow et al. [20] reported the thickness of remaining dentine on a maxillary second premolar following various preparations for a metal-ceramic or all-ceramic crown. The thinnest section of remaining tooth structure was the palatal wall with only 0.8mm and <0.3 mm remaining, respectively.

Many *in vitro* studies on endodontically treated teeth have examined the effect of the preserved coronal dentine height on the success of the final restoration. Maintenance of a height of at least 2 mm of coronal dentine has a favorable effect [21-23]. It has been also recommended that preserving a 2mm of coronal dentine thickness would improve resistance to fracture [24-26, 23].

Clinical evaluation of the remaining coronal dentine is essential in the restorative decision-making. A tooth restorability index (TRI) was devised to allow mapping of remaining tooth structure [21, 27]. This index allows assessment of tooth restorability by allocating a numerical value to tooth sections summing to a total value for the whole tooth. After all existing restorations and unsupported tooth structure have been removed; each molar tooth was divided into equal sextants: two proximal, two buccal and two lingual areas. A scoring system of 0–3 was allocated to each coronal dentine sextant (0=none, 1= inadequate, 2=questionable, 3=adequate) contributing to retention and resistance form. Thus, a maximum score of 18 could be given for each tooth and the topography of the remaining tooth can be recorded.

In their *in vivo* investigation to assess the remaining coronal tooth structure in teeth prepared for complete and partial coverage restorations, Murphy et al. [26] used 3D scanning and the TRI to assess teeth preparations for full and partial coverage restorations. They found there was a strong correlation between mean TRI and scanned volume of tooth structure. They also confirmed that partial coverage preparations removed less tooth structure than full coverage when provided for the same teeth.

Evaluation of remaining tooth structure should focus on both the quality/quantity of the remaining tooth structure and the available restorative options. With different amounts of remaining tooth structure, different types of restorations are recommended. In situations of minimal or no retention, adhesive restorations have a major advantage of bonding to both enamel and dentine [28]. Bonding to enamel is stable over time, but *in-vivo* [29, 30] and *in-vitro* [31] studies have revealed the limited durability of resin-dentine bonds [32]. Frassetto et al. [33] carried out a review about the durability of resin-bonded interfaces and their degradation with ageing and concluded that although most currently used dental adhesive systems show favorable immediate results reflected in good retention and sealing, dentine bonded interfaces may not withstand ageing and may show long-term degradation [34]. While, clinical trials evaluating adhesive systems have found dramatically variable bonding qualities between tested materials [35] and substrate [36, 37]. Given that dentine- adhesive bond varies among different condition and it deteriorates with time, reliance purely on adhesion may not be ideal.

Based on the aforementioned literature, it has been shown that loss of tooth structure within the coronal aspect of the tooth can alter stress distribution within a tooth. It has been well demonstrated that the fracture resistance of the restored teeth is lower than sound teeth. The combined effect of the quality and quantity of the remaining coronal tooth structure together with its exact dimension recommendations still need further evaluation. Therefore, the major aim of this research was to map and evaluate tooth strain in teeth with different amounts and areas of remaining tooth structure, and tooth surface loss utilising two techniques: the surface displacement field measured using Digital Image Correlation (DIC) and strain gauges (SG). The null hypotheses tested in this study were that: (i) there was no significant difference in strain in teeth with differing structural loss, and (ii) there was no difference in strain measured using 2 different techniques.

Methods and Materials:

Sample Preparation:

50 extracted, intact, non-carious human maxillary premolars were collected following consent (NHS REC Ethical approval no. 11LO/0939). Teeth were cleansed of soft tissue debris and stored in 0.2% thymol solution at 4°C [38-40, 1] until testing. The selection of teeth was based on regular crown anatomy, intact cusps, and lack of wear. Teeth of a similar size were selected by measuring the buccolingual (B-L) and mesiodistal (M-D) width in millimetres at the height of contour using a digital calliper to have the following average (B-L= 8.2mm, M-D= 6.4mm) ± 0.1 (Standard Deviation (SD)). Repeated:Each tooth was dried and mounted vertically in the centre of a (2.5 cm in height) nylon mounting mould using clear epoxy resin (Specifix-20; Struers Ltd). The latter was used according to the manufacturer's recommendations. Each root was positioned centrally with the long axis of the tooth aligned parallel to the mould walls. A 1mm height of the roots was left exposed below the cementum-enamel junction (CEJ), simulating the alveolar bone level. The epoxy resin was allowed to polymerize for 24 hours at room temperature before the mould was opened. The resin base was machined with water-cooled silicon carbide discs (220-grit) (LaboPol-5; Struers, Copenhagen, Denmark) to expose some of the root structure at the bottom of the base.

10 sound premolars served as control (Control). 40 premolars served as test and each was prepared into 2 samples (buccal and lingual walls) (n=80). Samples were divided into 2 subgroups (n=40) according to the composition of the prepared walls. One group was prepared to have both enamel and dentine elements in the remaining walls (E+De), while the other was prepared to have dentine only (De). Each group was further divided into 4 sets of dimensions according to the preparation height to width ratio of the 2 remaining cusps (n=10). The dimensions of 1mm and 1.5mm were selected to represent the width for (2:1 and 3:1) height to width ratio generating 4 preparation dimensions (A, B, C, D) as shown in (Table I).

Tooth preparation started as an MOD cavity, then cuspal walls were reduced in thickness at both outer and inner aspects following the outer contour of the tooth to the test dimensions (Table I) with a high-speed hand piece and constant water irrigation at 40 ml/min flow rate. A digital calliper was used constantly to check dimensions along

6 approximate points on the prepared wall (mesial, central, and distal points at both the incisal and cervical ends of each prepared wall). For initial preparation the FG 765X Coarse chamfer diamond bur (Kerr Blu White Coarse Diamond Bur, Henry Schein Europe) was used, followed by FG SF2 fine chamfer diamond bur (Kerr Blu White Diamond Bur FG Yellow, Henry Schein Europe) and finally with a tungsten carbide finishing bur (T/C Fine Finish 30 Blade, Henry Schein Europe). The base of each prepared sample wall was considered to be 1 mm above the CEJ. Teeth were lightly prepared as a slice preparation with no finish line cervically. The external walls were cut to be parallel with a maximum wall inclination of 6°-14° on buccal, lingual, and proximal aspects [41, 42] creating a total occlusal convergence (TOC) of 10°-20° [43, 44]. The inclination angles formed was determined by direct viewing of the preparation from all aspects (buccal, lingual and proximal). A dimple (1mm diameter and 0.5 mm depth) was prepared on the top of each wall to allow a point of loading at the centre of the wall (Figure 1). All preparations were made by one operator to ensure standardization.

To keep teeth moist after preparation, a damp cotton pellet soaked in thymol was placed over each tooth. Teeth were kept within a sealed plastic container resting on a thymol moist tissue to act as a humidor and refrigerated until ready for testing.

Displacement Measurements on Tooth Specimens:

Specimens were tested twice using two different methodologies: Digital Image Correlation (DIC) and with strain gauges under uniaxial compression tests.

Experimental Setup for Digital Image Correlation (DIC):

The specimens in the resin mount were placed in an Instron Electropuls E3000 machine (Instron, Norwood, Massachusetts, USA) which was programed to produce a load that was ramped within physiological limits for the human dentition from 5 N to 130 N and back to 5 N with 25 second dwells at 50 N, 70 N, 90 N, 110 N, and 130 N. The load was introduced into the dimple on the top of each specimen using a 2.5 mm ball bearing. A small pre-load of 5 N was used to hold the experimental setup in place before the test started and after the test ended.

A speckle pattern was painted onto the specimens using a black-ink spray as better quality DIC measurements could be obtained using this patterning method (Figure 3). The imaged face of the samples was kept dry for the duration of the test. Images were analysed and a displacement field determined.

Vertical displacement was measured in an area directly below the point of loading on the buccal/ palatal of the specimen. These data were averaged over a small width either side of the centre line and this was plotted against a vertical position within the specimens. Strain was recorded when it was constant at areas where appreciable linear relationship between displacement and vertical position were observed.

The buccal/palatal surface of the specimen was imaged using a macro lens that had a field of view of approximately 3 mm x 2 mm in a circular area caused by internal vignette of the image, (Figure 3). At this magnification, this corresponded to approximately 1800 pixels per mm or 1.8 pixels = 1 micrometre. Images were captured at peak load (130N) and final unload (5N) and these were used to measure displacement. The displacement field was processed in several ways to calculate strain over appropriate fields of view, either a long narrow width representative area or a shorter vertical height where linear strain behaviour was observed.

Experimental Setup for Strain Gauge Testing:

Strain gauges (Micro-Measurements Group UK Ltd) attached to copper leads, with a resistance of 120Ω (type C2A-06-062LW-120), and a gauge factor of 2.15 were attached to prepared samples. The surface of each tooth was prepared by etching with 37% phosphoric acid (Heraeus, i Bond Etch 35 Gel, Germany). Enamel was etched for 30 second followed by a 15 second dentine etch. The surface was washed with water for 20 seconds and dried with a stream of air for 10 seconds. The backing of the strain gauges was bonded to the prepared buccal and lingual walls of premolars with a thin layer of cyanoacrylate adhesive (M-Bond 200 Adhesive; Micro-Measurements Group UK Ltd). Care was taken to align the gauges vertically along the long axis of the tooth so that they were parallel to the direction of loading. After the adhesive had set, the gauges were covered with a thin layer of a silicone rubber protective coat (M-COAT C, Micro-Measurements Group UK Ltd). All test and control samples received strain gauges and an extra control tooth received a dummy gauge that was subjected to the same environmental conditions but without loading.

The resin block containing the specimen (Figure 2) was screwed into a brass receptacle within a servohydraulic testing machine (Dartec series HC10, Dartec Ltd) with a 1.0 kN load cell. The loading programme was initially set in the test machine; the subsequent loading cycles were controlled by the testing machine software (Workshop 96. Dartec HC10; Zwick Ltd). Samples were subjected to the same gradual loading and unloading cycles as previously described for the DIC testing and strain values were recorded at peak load (130N).

Results:

The goal of the analysis was to determine the influence of the two factors involved in this study: tooth composition and dimensions of the remaining tooth structure. Two tooth compositions were tested (E+De and De) and four height to width (H:W) dimensions (A=2:1mm, B=3:1mm, C=3:1.5mm, D=4.5:1.5mm). Data of tested strain under gradual loading and unloading were analysed with a 2-Way Analysis of Variance. Bonferroni post hoc test was applied. Groups were considered statistically different at $\alpha = .05$.

Digital image correlation (DIC):

A typical image from a measurement is shown in (Figure 3). Here the position of the loading ball can be seen at the top of the image. The speckle pattern is clearly visible. The area at the bottom of the image is partially embedded in resin and behaved differently under load to the bulk of the specimen.

The area used for the measurement is demarcated as a red box in (Figure 3). The data were averaged over a small width either side of the centre line and this was plotted out against vertical position within the specimen. For many specimens there were appreciable areas where a linear relationship between displacement and vertical position was observed and the strain was constant within these areas and was recorded. A displacement field, in micrometres is shown as an example in (Figure 4). This was generated by using the relative movement between two images to measure in-plane displacements of one image against another. The images used for this were fully-loaded with subsequent unloading.

The two-way ANOVA indicated a statistically significant difference in the mean strains between the different preparation dimensions (A, B, C, D) ($p<.05$) but not between the compositions (De, E+De) Table II. Dimension A showed a significantly higher strain than C & D. While, Dimension D showed significantly lower strain than A & B. No significance was detected between dimensions B & C or C & D. Displacement in Control samples were too low to be recorded by the DIC system.

Comparison between the estimated mean strain values and their associated standard deviation for all groups (A, B, C, D) at both Dentine (De) and Enamel+Dentine (E+De) compositions are shown in (Figure 5).

Strain Gauges (SG):

The 2-way ANOVA indicated a statistically significant difference in the mean strains both between the different preparation dimensions (A, B, C, D) (p<.05) and between the 2 composition groups (De, E+De) (Table III). For both composition groups (De, E+De), all dimensions were statistically significantly higher than control. Dimension (A) showed significantly higher strain than all other dimensions. While, both dimensions B & C had significantly lower strain than A and higher than D (p<.05).

Comparison between the estimated mean strain values and their associated standard deviation for all groups (A, B, C, D) at both Dentine (De) and Enamel+Dentine (E+De) compositions are shown in (Figure 6). Comparison of the mean strain values between (De) and (E+De) for all groups with (SG) testing is shown in (Figure 7).

Discussion:

In the present study, teeth were subjected to gradual non-destructive occlusal loading within the physiological limit for human teeth followed by unloading in order to try to mimic a clinically relevant loading pattern. Teeth were prepared according to 4 sets of dimensions involving different height to width ratios. The resulting walls followed the natural convexity of the buccal and palatal tooth surfaces. To standardize preparations, the radius (R) of the convex walls was calculated to have an average value of 3.25mm ±0.15 (SD) according to the following equation

$$R = \frac{\left(\frac{X}{2}\right)^2 + H^2}{2H}$$

Where X is the mesiodistal width of the convex wall and H is the depth of the convexity.

Before testing, the resin base of all samples was machined to expose some of the root structure. This was designed in this way so that on loading, only micromotion occurred.

DIC is an innovative non-contact optical methodology to measure strain and displacement. It uses the relative movement between two images to measure in-plane displacements. The effect of the size of the tooth specimen under load was incorporated by calculating bulk modulus for each sample from the zone where linear strain behaviour has been recorded. This was done to overcome the inevitable size variations expected to occur between samples as they were hand-prepared, not machined.

Some areas of the image appear noisy (Figure 4), this is due to the out of focus areas and spatial variations in the speckle pattern. The central area across the image was chosen to overcome the noise and maximise the area for the measurement that was in focus (Figure 3). DIC can measure displacements at a resolution down to about 1/20th of a pixel or in this case about 10 nanometres. However, the limitation of the optical system can be seen as the very limited depth of field and areas away from the centre of the image, that are out of focus, are less suitable for DIC measurements. This may explain the failure of the system to detect the very low displacement expressed by control samples and for this reason they were excluded from testing.

Fabrication of indirect restorations usually includes tooth preparation to reshape the remaining tooth structure. There is little published data on the optimal thickness of remaining dentine in preparation walls. Different heights of remaining coronal walls (0 to 5mm) and widths (0.5 to 4mm) have been tested in both vital and non-vital teeth [45-49].

Many studies have been carried out to look at coronal dentine height, without consideration of width [45, 50, 40, 48, 49] root dentine thickness [51, 47, 52], remaining coronal tooth structure location [46, 26, 53], or a combination of these [54].

The aforementioned studies had different designs, looked at different parameters, and lacked a common standardization with most being carried out *in vitro* and little work being undertaken *in vivo.* So far, however, there have been no controlled studies which define specific recommendations on height to width dimensions and locations of remaining tooth structure to best withstand stresses and resist fracture. By that, this study is considered the first to evaluate remaining tooth walls with a specified height to width ratio.

Seow et al. [20] found that following tooth preparation for a ceramic inlay and onlay, the width of 2.0-2.5mm of buccal and palatal tooth structure was remaining. While, following preparation for a metal-ceramic crown, approximately 1mm of tooth structure was left buccally, and between 1.6mm-1.8mm palatally. On the other hand, preparation for an all-ceramic crown retained 1.0mm-1.2mm of tooth structure surrounding the endodontic access cavity. The effect of these varying dimensions is unknown.

Another study by Davis et al. [55] developed a method to measure local dentine thickness using x-ray micro-tomography scans. Scans were made on extracted upper central incisors before and after preparation for metal ceramic crowns. Their results revealed multiple thicknesses of residual dentine along different prepared crown areas ranging between 0.5mm (the thinnest), and 1-1.5mm (the thickest). Following the aforementioned studies as a guide and considering the size of human posterior teeth and the space occupied by the pulp, the thickness of 1mm and 1.5mm were selected to represent the most common range. In order to assess the possible influence of height and width combinations, these dimensions of remaining wall thicknesses were prepared against multiple wall heights to produce the height: width ratios of 2:1 and 3:1.

In our study, tooth preparation was started as an MOD cavity to create buccal and lingual samples in each premolar. To standardize dimensions, the depth of the mesial and distal cavities was positioned 2mm coronal to the CEJ. The height of the buccal and lingual walls (samples) was measured coronal to an imaginary line positioned 1mm above the CEJ (equivalent to the position of the gingival margin) as Bandlish et al. [21], used the gingival finish line to assess the remaining tooth structure coronal to this level. This was designed in order to prevent pulpal exposure and to simulate a clinical approach to avoid encroaching on the biologic width.

Different dimensions and qualities of remaining tooth structures were investigated; no attempt was made to restore the teeth to their original form. The influence of the use of either direct or indirect restorations with or without dentine bonding systems was not investigated in this part of the study. The combination of dentine adhesive systems and resin luting cements have shown the ability to strengthen the restored tooth units [56-59]. Bonding intracoronal restorations offers cusp splinting and decreases cuspal flexure, thus strengthening the remaining tooth unit [60, 59].

Samples in this study were tested as independent walls of remaining tooth structure without the incorporation of a finish line or investigation of the effect of 'ferrule' if these teeth were restored. The incorporation of the 'ferrule' concept is considered one of the foundations of restoration of vital and endodontic treated teeth [61, 53]. Adhesion to the prepared walls or overlaying of the cusps would have altered the results of this study. This study was designed to examine the effects of remaining type and dimensions of tooth structure alone.

Destructive mechanical tests can be used in situations of high intensity load application, to determine fracture resistance and analyse tooth behaviour. However, these tests show limitations in obtaining the valuable internal behaviour of the tooth restoration complex. For a more reliable response, a combination of non-destructive methodologies has been implemented [62, 17, 63]. The implementation of non-destructive testing methods allows sequential and repeated measurements on the same tooth, taking into consideration the individual differences among teeth, which further minimizes the effects of the natural variation between teeth [38].

Based on these results, the null hypothesis that there would be no significant difference in tooth strain with different structural loss could be rejected. The results of both DIC and strain gauge testing methodologies showed significant difference in strain values between some of the geometries tested (A, B, C, & D). (E+De) group showed generally lower strain values than (De) at all dimensions tested with strain gauges. This is most likely due to the stiffening effect enamel has on dentine albeit its minimal dimension in (E+De) groups when compared to the presence of dentine only in (De) groups. However, significant difference between the two compositions could be detected only when strain gauges were used. This could be attributed to the reliability and accuracy of the strain gauges mounted directly on the tooth structure, in measuring relative stress/strain. The role of enamel in resisting and dissipating strain may be particularly important to patients who have lost enamel due to attrition, ageing, or trauma.

Since both testing methodologies gave similar result patterns, the null hypothesis that there was no difference in strain measured using 2 techniques can be partially accepted. In both methodologies, group (A) possessing the smallest height and width (2:1mm) showed the highest strain and were significantly different to both grou*p*s (C) & (D) (3:1.5mm & 4.5:1.5mm) respectively. These results suggest the importance of the height to width ratio in the preparation, and that by preserving a minimum height of 3 mm and a width between 1-1.5 mm lower strain is achieved.

This study's findings with regards to remaining tooth width agree with the results of Shahrbaf S, Shahrbaf B, Mirzakouchaki SS, Oskoui MA and Kahnamoui [64] who found that fracture resistance of endodontically-treated teeth with composite restoration could be reduced by preserving a mesial marginal ridge thicknesses of 2mm, 1.5mm and 1mm. However, preserving a 0.5mm thickness of the mesial marginal ridge did not provide fracture resistance at the level of intact teeth, yet it conferred higher strength than teeth with no marginal ridge at all.

The results also accord with earlier observations by AL-Omiri and A. AL-Wahadni [65], who investigated the effect of different heights of remaining coronal dentine on the fracture resistance of root canal treated teeth restored with composite cores. Although results were not statistically significant, greater fracture resistance was achieved with greater retained dentine height. However, the fracture pattern of teeth was not related to the height of retained dentine when the height was >2 mm. The positive influence of maintaining 3mm of tooth structure was also confirmed by Al-Wahadni A and Gutteridge D [45].

Magne P [15] and Magne et al. [66] have tested the response of both anterior and posterior teeth under different loading configurations. The authors concluded that progressive loss of tooth substance (MO to MOD to ENDO) produced a progressive loss of cuspal stiffness. They also confirmed that linear axial loading of posterior teeth did not generate harmful concentrations of stress compared to lateral loading. However, the behaviour of posterior teeth must be differentiated from the behaviour of anterior teeth due to shape and occlusal loading patterns. Stress distribution within an incisor was not significantly affected when the tooth material was removed proximally, whereas, a significant increase in stress concentration and flexibility occurred when facial and palatal tooth material was removed [67, 68].

This is an *in vitro* study so it cannot replicate the clinical situation although it was designed to replicate the clinical environment as closely as possible.

Conclusions:

Within the limitations of this study it was concluded that;

The preservation of a remaining minimum tooth height of 3 mm and a width of 1-1.5 mm produced lower strain upon loading than 2mm tooth height. Remaining tooth structure, comprised of both enamel and dentine, resisted strain under load better than dentine only counterparts at all test dimensions when evaluated with strain gauges. The results obtained with strain gauges and DIC showed similar trends. DIC is a relatively simple optical methodology that allows measurement of strain and displacement without the need for physical attachment to the object.

Recommendations:

This study has looked into the effect of different remaining tooth structure dimensions (multiple heights to width combinations) under axial static loading. The effect of tooth loading with and without the presence of a restoration (either bonded or cemented) should be further studied.

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Figures:

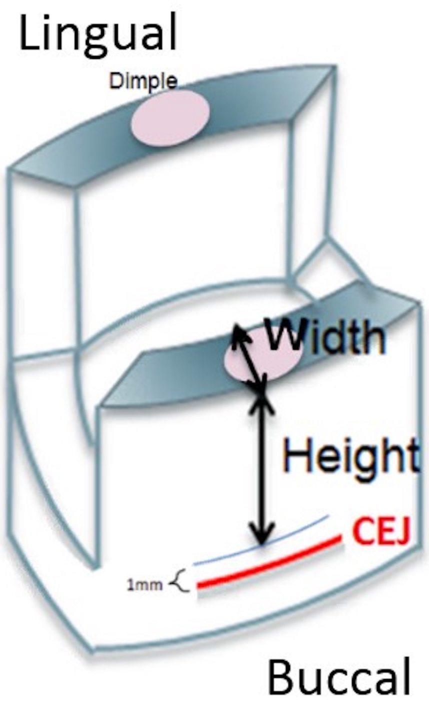

Figure 1. A diagram of the prepared tooth.

Figure 2. A mounted prepared tooth.

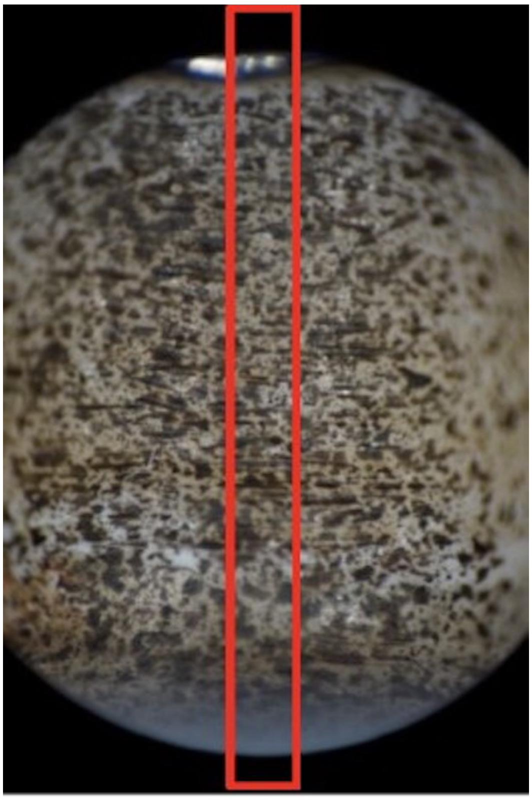

Figure 3. A typical image used for displacement field measurement.

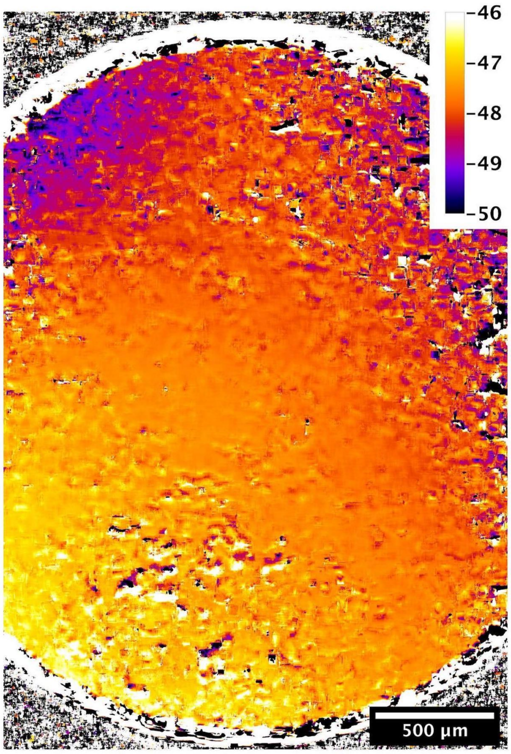

Figure 4. A full field displacement measurement using DIC showing movement in the vertical direction, the pixels increase from top to bottom. The scale is in micrometres.

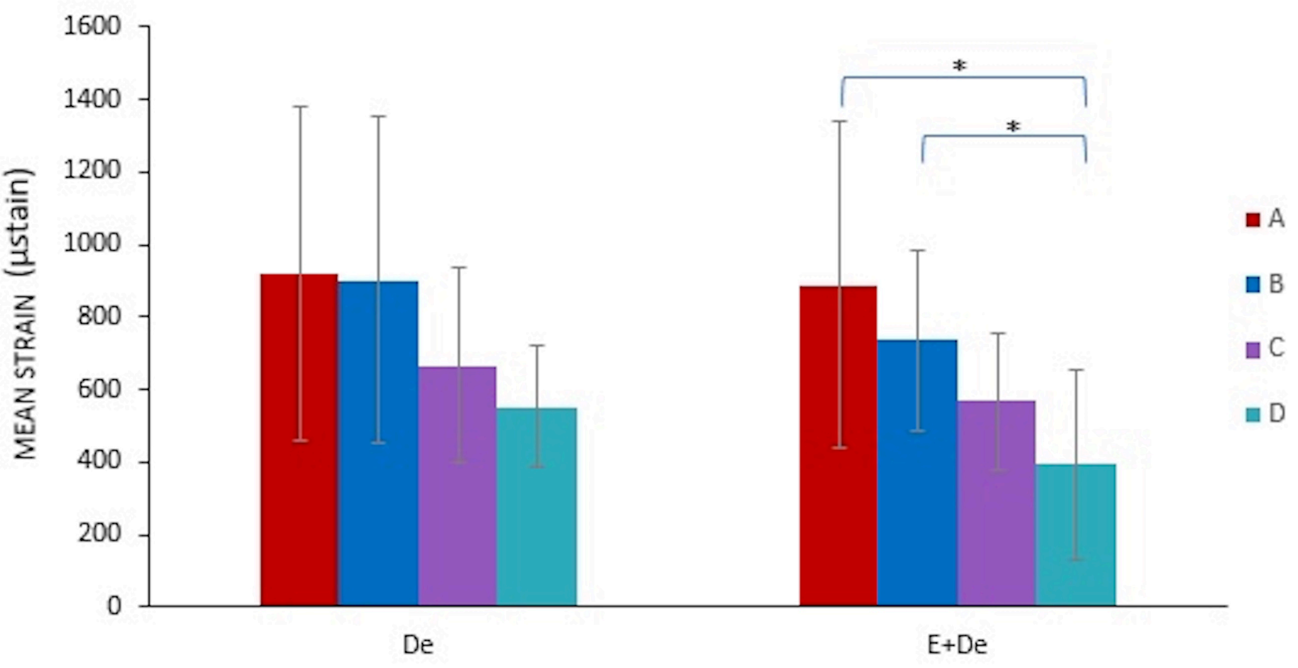

Figure 5. The mean strain values for all the groups± standard deviation with Digital Image Correlation (DIC) testing for both Dentine (De) and Enamel+Dentine (E+De) groups. *n*=10 per group (**p*< 0.05). A, (Height to Width ratio (H:W) = 2:1mm). B, (H:W= 3:1mm), C, (H:W= 3:1.5mm), D, (H:W= 4.5:1.5mm).

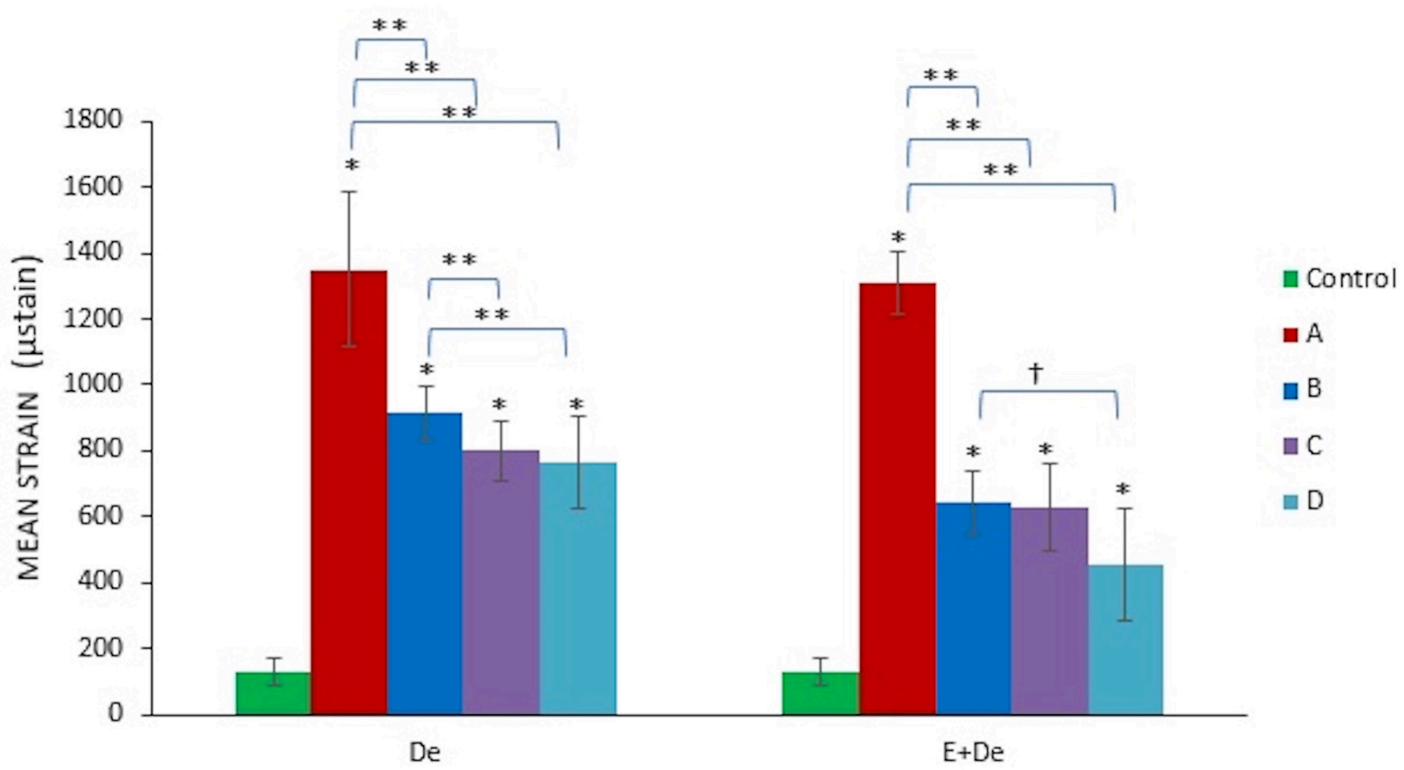

Figure 6. The mean strain values for all the groups± standard deviation with Strain Gauge (SG) testing for both Dentine (De) and Enamel+Dentine (E+De) groups. n=10 per group (*p< 0.001 statistical difference with respect to the control), (**p<0.001 statistical difference between groups), (†p<0.05 statistical difference between groups). A, (Height to Width ratio (H:W) = 2:1mm). B, (H:W= 3:1mm), C, (H:W= 3:1.5mm), D, (H:W= 4.5:1.5mm).

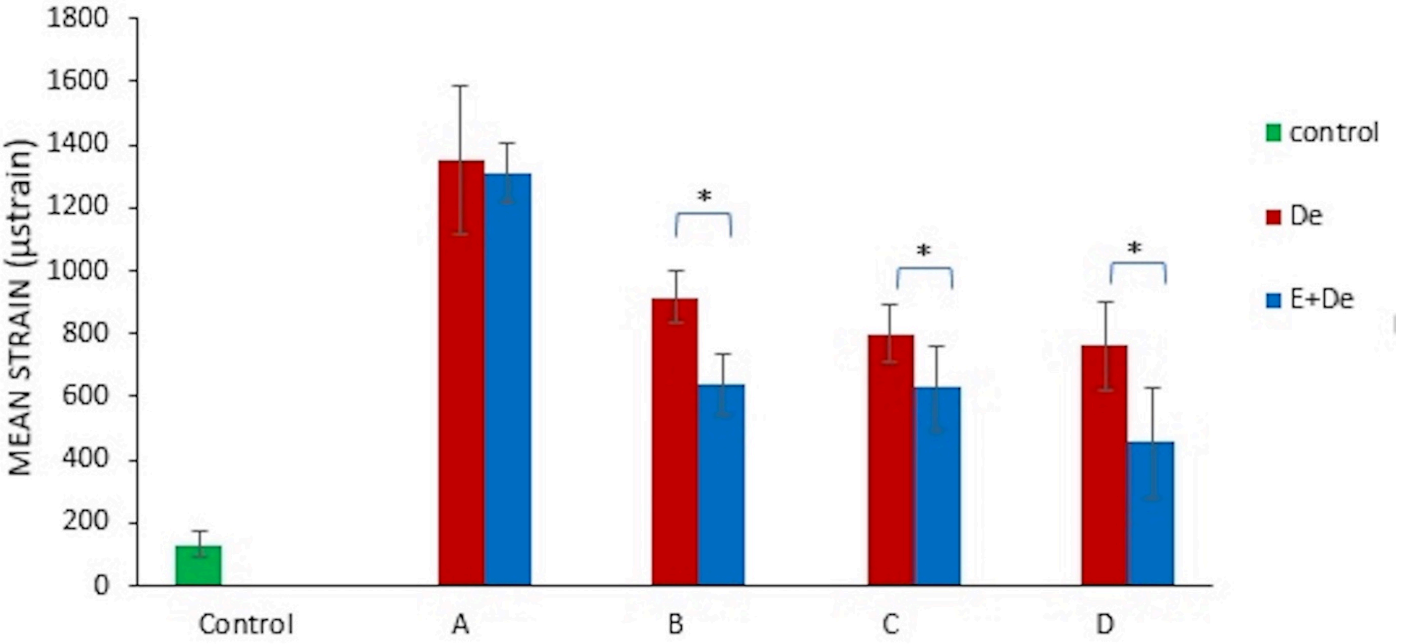

Figure 7. Comparison of the mean strain values between Dentine (De) and Enamel+Dentine (E+De) for all groups± standard deviation with Strain Gauge (SG) testing. n=10 per group (*p<0.05 statistical difference between groups). A, (Height to Width ratio (H:W) = 2:1mm). B, (H:W= 3:1mm), C, (H:W= 3:1.5mm), D, (H:W= 4.5:1.5mm).

Tables:

Table I. Sample preparation dimensions:

Wall Width	(H:W mm) 2:1	(H:W mm) 3:1
1mm	2:1 (A)	3:1 (B)
1.5mm	3:1.5 (C)	4.5:1.5 (D)

H = Height of prepared wall

W= Width of prepared wall

Table II. Tests of Model Effects (DIC)

Source	Wald Chi-Square	Degree of freedom (df)	Sig.
Dimension	27.055	3	*.000*
Composition	2.804	1	.094
Dimension * Composition	.559	3	.906

Dependent Variable: strain

Model: Dimension, composition, Dimension * Composition

Table III: Tests of Model Effects (SG)

Source	Wald Chi-Square	Degree of freedom (df)	Sig.
Dimension	796.506	3	*.000*
Composition	100.733	1	*.000*
Dimension * Composition	26.801	3	*.000*

Dependent Variable: strain

Model: Dimension, Composition, Dimension * Composition

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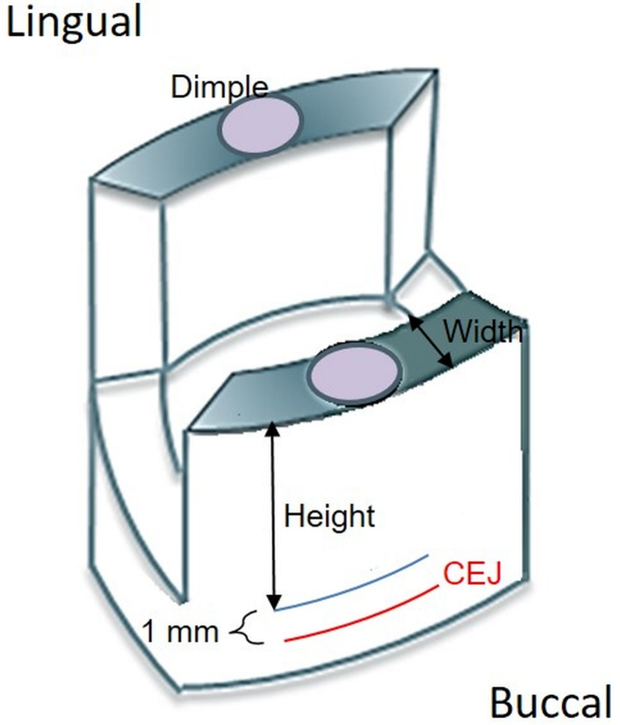

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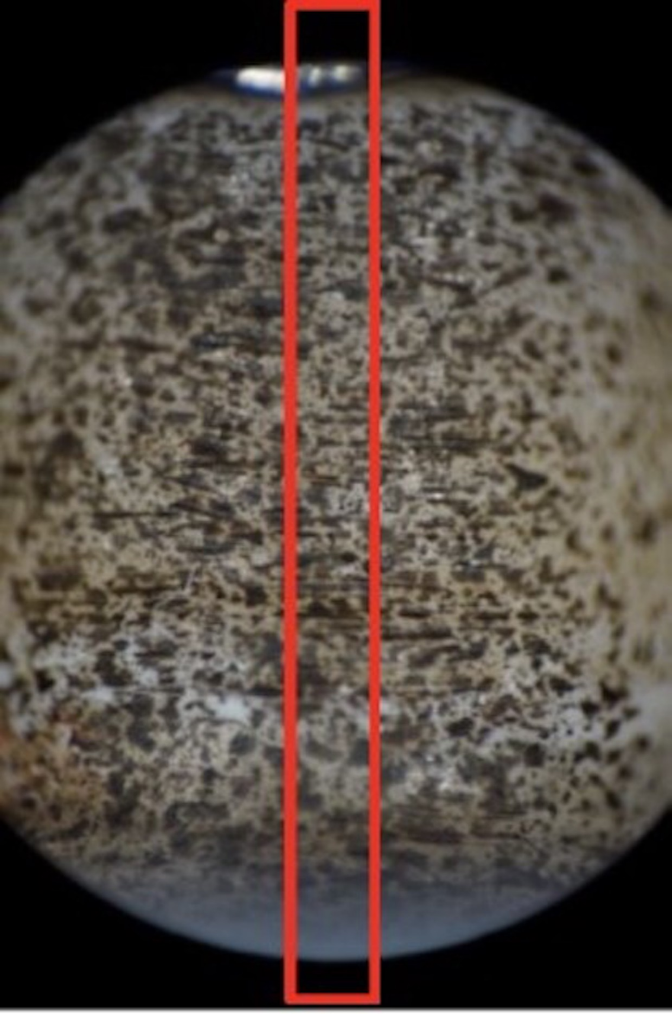

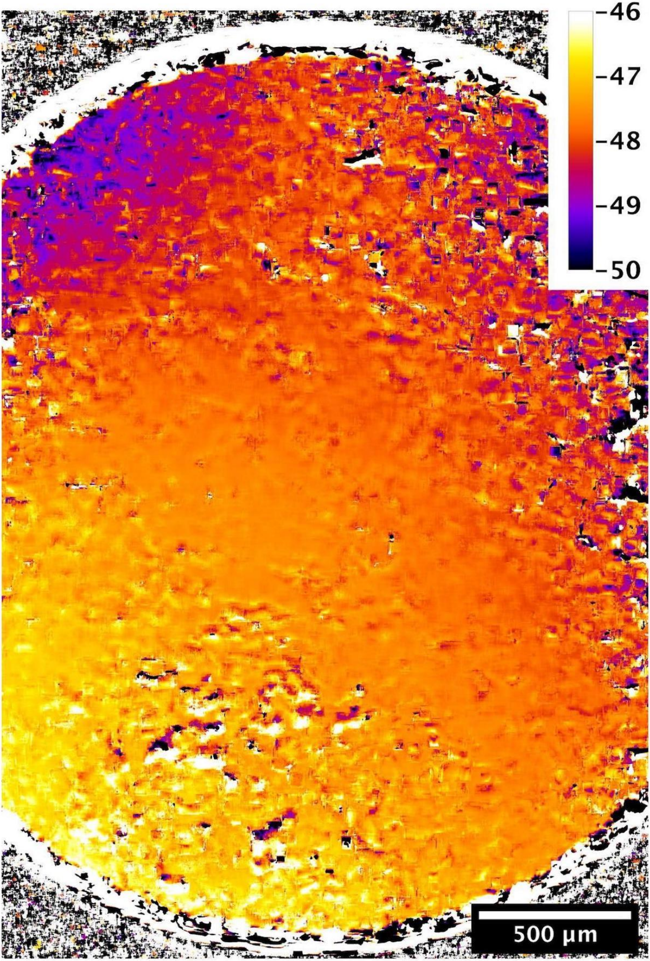

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-49
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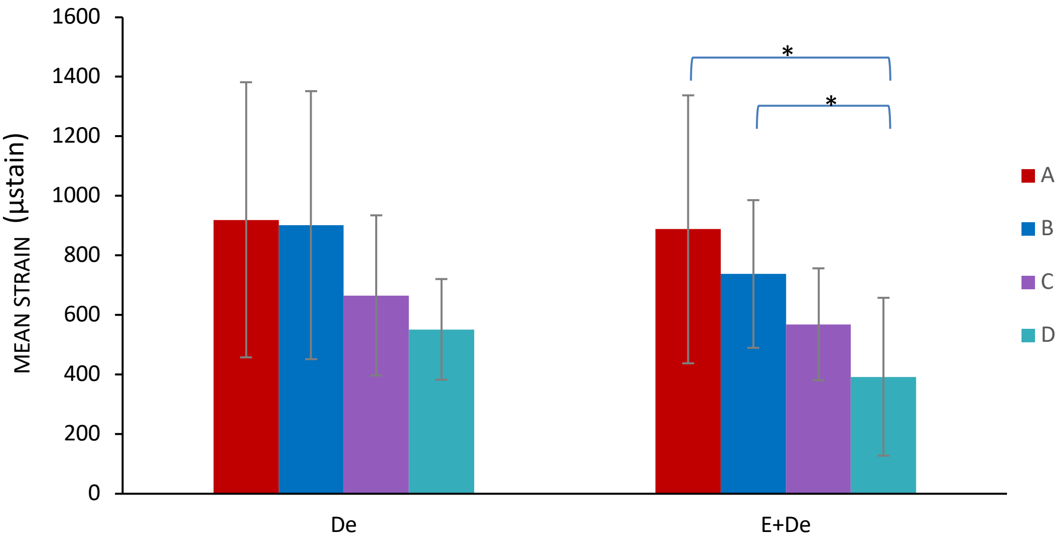

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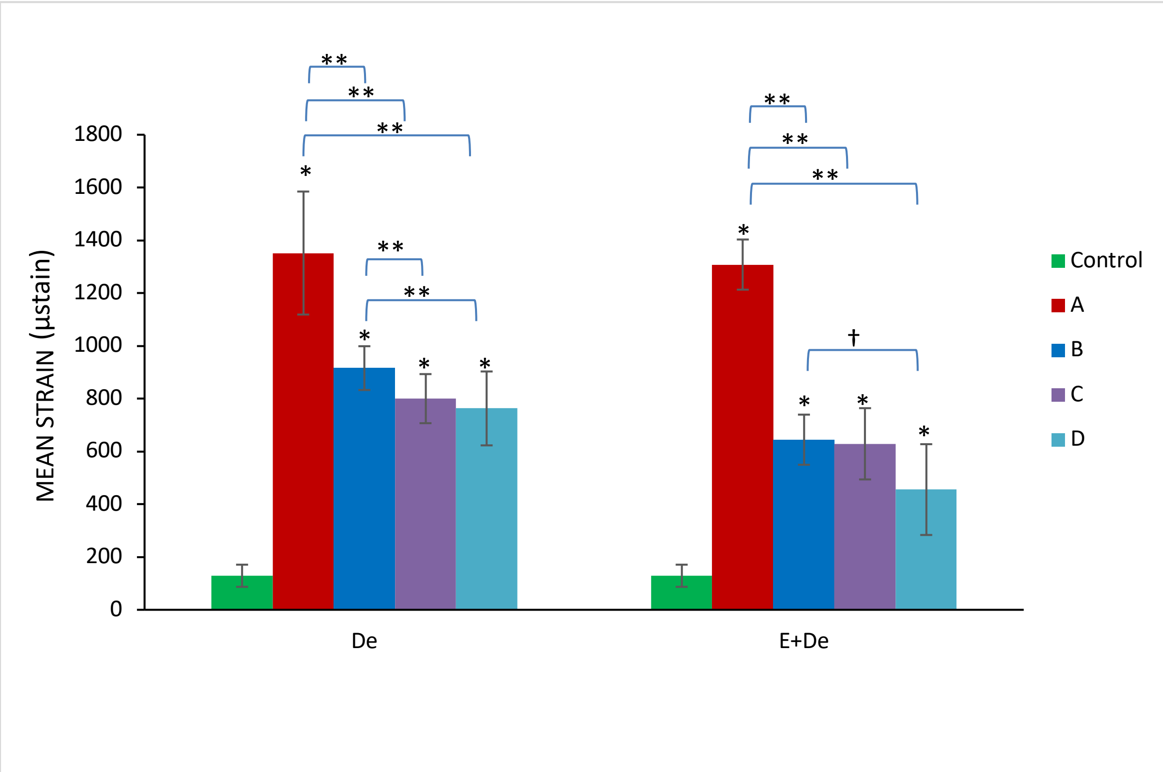

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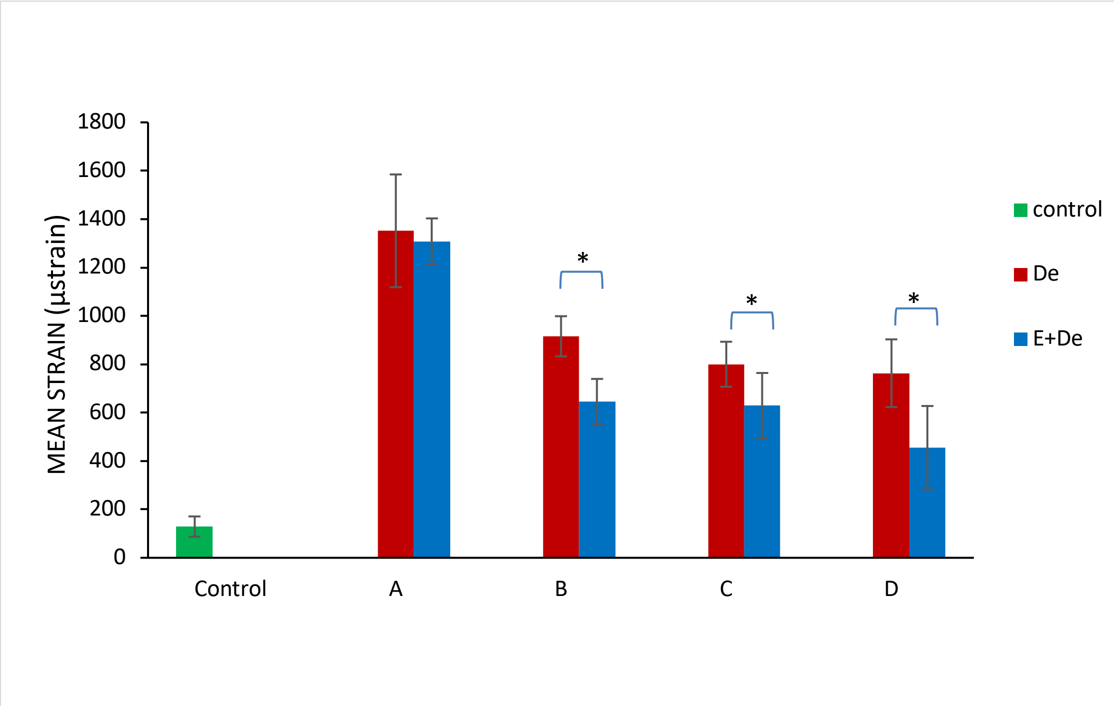

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