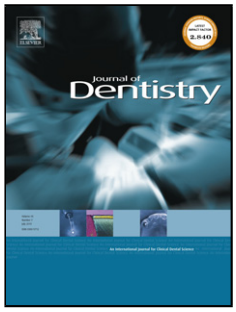

Title: The effectiveness of adhesives on the retention of mandibular free end saddle partial dentures: an *in vitro* study

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The effectiveness of adhesives on the retention of mandibular free end saddle partial dentures: an in vitro study

Short title: *In vitro partial denture adhesive model*

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Abstract

Objectives: Existing *in vitro* methods for testing denture adhesives do not fully replicate the complex oral geometries and environment; and *in vivo* methods are qualitative, prone to bias and not easily reproducible. The purpose of this study was to develop a novel, quantitative and more accurate model to test the effect of adhesives on the retentive force of mandibular free end saddle partial dentures.

Methods: An *in vitro* model was developed based on an anatomically accurate cast of a clinical case. Experimentally, the amount of adhesive was varied (0.2g-1g) and the tensile force required for displacement was measured. Different commercially available adhesives were then tested at the optimum volume using the *in vitro* model. A 3D finite element model of the denture was used to assess how the forces to induce denture displacement varied according to the position of the force along the saddle length.

Results: The mass of adhesive was found to significantly alter retention forces, with 0.4-0.7g being the optimum range for this particular scenario. Use of adhesives significantly improved mandibular free end saddle partial denture retention with the worst performing adhesive increasing retention nine-fold whilst the best performing adhesive increased retention twenty three-fold. The finite element model revealed that 77% more force was required to displace the denture by positioning forces towards the mesial end of the saddle compared to the distal end.

Conclusions: An *in vitro* denture adhesive model was developed, which demonstrated that mass of adhesive plays a significant role in enhancing denture retention and supported the design principle of placing as few teeth as clinically necessary on the distal end of the free end saddles.

Keywords: Denture; ; ; ; ; , adhesive, in vitro, model, finite element, acrylic

Clinical significance: Limiting the position of teeth on free end saddles to the mesial and mid portion of the saddle will reduce displacements caused by mastication. The movement of mandibular free end saddle partial dentures can be restricted with the use of denture adhesives. Altering the mass of adhesive used can further improve the retention of mandibular free end saddle partial dentures for patients.

Introduction

The ability of a denture to resist vertical displacement away from tissues, also known as denture retention, is an important factor for the success of the prosthesis. Excessive movement, induced by vertical tensile forces, can cause pain, tissue damage and discomfort to the denture wearer. A review by Darvell et al. [1] highlighted the importance of surface tension, viscosity, time, base adaptation, border seal, seating force and soft tissue quality in the retention of dentures, whilst other factors, such as atmospheric pressure vacuum, adhesion, cohesion, wettability, surface roughness, gravity and muscular control were not considered important in retention. Previous studies however have highlighted the benefits that denture adhesives have in preventing the movement and enhancing the retention of complete dentures [2-6].

Denture adhesives have been available since the 1930s [2]. These materials were marketed exclusively to complete denture wearers to increase their confidence in wearing dentures by improving the level and consistency of retention. The 2009 Adult Dental Health Survey [7] showed that the number of partially endentulous patients is increasing in the UK and this is leading to an increase in the number of people wearing partial dentures. A 10 year clinical evaluation of removable partial dentures however highlighted a high failure rate of partial dentures ranging from 66.7% for clasp-retained removable partial dentures to 33.3% for conical crown-retained dentures [8]. Furthermore a patient satisfaction study on partial removable dentures demonstrated the most frequently encountered complication in association with partial removable dentures is the loss of retention, causing dissatisfaction of patients related to chewing ability [9]. This recent increase in denture wearers and patient dissatisfaction has led to adhesive manufacturers releasing products specifically aimed at partial denture wearers.

The subject of denture retention has been the focus of a number of *in vitro* studies and *in vivo* clinical investigations [2-6]. *In vitro* methods for testing denture adhesives however are over simplified and do not fully replicate the complex *in vivo* geometries and environment, which may lead to inaccurate predictions of clinical performance. Similarly *in vivo* testing employs performance indexes (e.g. Kapur Index) and functional tests which are qualitative, prone to bias and not easily reproducible.

Previous literature has focused on investigating retention of complete dentures [3, 10] and in particular maxillary complete dentures [4-5]. It is only recently that mandibular denture retention has been investigated [6]. This was a logical step in light of recent evidence that a high percentage of patients are dissatisfied with the retention of their mandibular complete denture [11]. Given the recent shift in marketing focus of denture adhesives towards partial dentures, it is vital to investigate whether any significant retention can be gained from their use.

The cases that suffer from the most problems with support and retention are removable partial dentures [12]. This is due to the differences in compression of the mucosa and the periodontal ligament that allows rotation on loading and the differences in retention forces between the clasp on the abutment and the peripheral seal around the saddle that allows rotation around the distal abutment tooth when forces away from the tissue are applied. Currently, adhesive manufacturers have limited quantifiable methods or evidence to estimate how effective their adhesive products could be for the retention of mandibular free end saddle partial dentures.

When planning to restore a mandibular free end saddle it is important to consider a shortened dental arch (SDA). SDA therapy will not be suitable for all patients and case selection is important because failure can compromise future treatment options [13]. If the patient does require a removable partial denture, maximum retention can be achieved by using a tooth and mucosa borne denture

design including an RPI system (mesial rest, distolingual guide plate, I-bar) and indirect retention where applicable [14]. In cases where retention is not optimal, the free end saddle has a tendency to drift and rotate around the implant/abutment causing discomfort and potentially injuring soft tissues [12-15]. There is evidence to suggest that 20% of free end saddle partial denture wearers are dissatisfied due to comfort and functional problems and in some cases this has led to patients not using the dentures over prolonged periods [16].

An argument could be made that, in a worst case scenario situation which combines unfavourable anatomy, poor ridge form and decreased neuromuscular control of the patient denture, an adhesive may prove to be an acceptable solution for the patient and clinician.

Denture adhesives are made up of synthetic polymers, antibacterial agents, preservatives, fillers, wetting agents and flavouring agents [17]. The synthetic polymers hydrate when they come into contact with saliva. This increases their volume which helps to fill the voids between the denture and mucosal tissues. The difference in viscosity between the hydrated polymer and saliva helps to increase the denture's retention [17, 18]. The synthetic polymers also form molecular cross-links which increase the cohesive forces within the adhesive [19]. Denture adhesives are potentially less effective in poorly fitting dentures because these dentures will require a thicker layer of adhesive to fill the void between the denture and mucosal tissues and this, in turn, will allow a faster ingress of saliva and air [17].

The aim of this study was to develop a novel, quantitative and more accurate model to test the effect of adhesives on the retentive force of removable partial dentures. This will be achieved by: assessing if mass of adhesive plays a role in retention of mandibular free end saddle partial dentures; assessing how effective different commercially available denture adhesives are at improving the retention of these dentures; and establishing the tensile load required to induce a 1mm vertical displacement from the ridge at different positions along the saddle. Therefore the null hypotheses are: the mass of adhesive will not affect vertical displacement force; the use of commercially available adhesives will make no significant difference to the vertical force required to displace the mandibular free end saddle from the ridge; and the tensile load to induce a 1mm vertical displacement will not significantly vary as the position along the saddle length changes.

Materials and methods

A clinical case with the minimum level of retention was chosen (Kennedy's class II), where there was only one guide plane and a negligible amount of undercut on the abutment tooth. For this study, no direct retention (clasp) was employed to simplify the model and to be able to measure the effect of the adhesive on retention alone. The denture framework used was composed of acrylic only, with no cobalt chrome frame. This allowed the results to estimate the percentage improvement in retention that adhesives can potentially achieve in this worst-case scenario situation. The clinical case mandible master impression was poured using Labstone Dental Stone (Dentsply, Surrey, UK, Figure 1). The cast was duplicated to avoid wear-related issues arising from repeated testing and cleaning protocols. The mandibular free end saddle baseplate was constructed from Selectaplus standard acrylic (Dentsply, Surrey, UK). A displacement loop was placed into the mid-point of the free end saddle area in order to connect the saddle to the displacing force (Figure 1). Two more identical mandibular free end saddle baseplates were constructed with displacement loops at the mesial and distal ends of the saddle.

To assess the mechanical retention force, a Lloyd LF-Plus materials testing machine (Ametek, West Sussex, UK) was used to apply a vertical tensile force at a cross-head speed of 50mm/min. Previous literature has determined that this is approximately the speed which occurs clinically in normal function [20] and is the speed widely employed by other studies allowing for direct comparisons to be made with other results [21-23]. The vertical tensile force was applied to the

baseplate through rigid steel wires connected to the displacement loop (Figure 2). Rigid steel wires ensured negligible elastic deformation when loading the baseplate. In this experiment the force was placed at the mid-point of the saddle.

To determine whether adhesive mass had an effect on denture retention, the displacement force was measure when using 0.2g to 1.0g of Polygrip® adhesive (GlaxoSmithKline, Waterford, Ireland) . The starting amount was approximately equal to that indicated by the visual representation on the manufactures instructions (0.2g). To simulate the oral environment, 1mL of water was applied evenly to the free end saddle area of the cast prior to applying the adhesive according to the manufacturer's instructions. The baseplate was pressed into place with even pressure for 10 seconds; this force was not measured but was applied by the same operator each time. The adhesive was then left for a further 5 minutes before the displacement force was applied. Sample size was estimated using a power calculation (Equation 1), where SD was the standard deviation obtained from a pilot study testing five samples using the manufacturer's recommended amount (Polygrip® adhesive, 0.2g) of adhesive (±2.3N); $Z^{\alpha/2}$ is 1.96 arising from a 95% confidence of avoiding a type I error (based on Z-table); Z^{φ} is 0.842 corresponding to 80% power (based on Z-table); and d, the effect size, is 3N (considered a clinically significant change in retention force based on a study by Kumar et al. [24]). Based on this calculation, ten measurements were taken for each mass of adhesive and the mean values calculated to establish statistically significant differences.

$$Sample\ size = \frac{2 \times SD^2\ (Z^{\alpha/2} + Z^{\varphi})^2}{d^2} \qquad [1]$$

Vertical retention was assessed for 5 different experimental groups; the control (without adhesive) and four different commercially available adhesives (Table 1). For the control group the baseplate and cast were soaked in water for 10 minutes and an additional 1ml of water was applied to the free end saddle area prior to firmly attaching the baseplate into place and loading. The following methodology was used for each of the 4 adhesives. In order to simulate the oral environment the optimum mass of adhesive (0.6g) was premixed with half its weight in water and left for 5 minutes before being applied to the baseplate. One mL of water was applied evenly to the cast's free end saddle area. The baseplate was pressed into place with an even pressure for 10 seconds. The adhesive was then left for a further 5 minutes before the displacement force was applied.

To determine how much force is required to vertically displace the denture by varying the position of the force along the saddle, a 3D model was constructed using a Renishaw DS30 laser scanner with Renishaw Dental Studio software (Renishaw PLC, Gloucestershire, United Kingdom). When a vertical displacing force is placed on the free end saddle, the baseplate establishes a fulcrum at its more mesial point of contact with the anterior teeth and rotates around this fulcrum. The 3D model was used to indicate the position of the fulcrum against the anterior teeth for this case (Figure 3). Several points were selected along the saddle, perpendicular to the fulcrum for finite element modelling (Figure 4). The model was imported into SolidWorks (Dassault Systèmes, MA, USA), a mesh was applied and the model was assigned material properties representative of acrylic (Table 2). The model was constrained along the fulcrum and the force at 21, 27, 33, 37.5 and 42mm from the fulcrum along the saddle required to create a 1mm vertical displacement at these points was modelled. The model was validated experimentally by applying 1mL of water to the cast followed by 0.2g of Polygrip® adhesive (to reflect the amount recommended by the manufacturer, GlaxoSmithKline, Waterford, Ireland) to the denture and testing the retention force at the mesial, mid-point and distal end of the saddle (approximately 21, 33 and 42mm from the fulcrum respectively).

Statistical analysis was performed using SPSS (IBM, NY, USA). Means, standard deviation, standard error and upper and lower confidence intervals were calculated for the control and adhesive samples. A two-sample T-test assuming equal variances was carried out to establish statistically significant differences between each of the test groups.

Results

Figure 5 shows the results of varying adhesive mass on retention force. The optimum mass of Polygrip® denture adhesive to achieve maximum retention ranges from 0.4-0.7g. Table 3 shows the results from the statistical analysis. Too little adhesive and the force required to displace the denture drops significantly (0.2g vs 0.4-0.7g, $p<0.05$). Similarly, too much adhesive can also result in significantly lower retentive forces when compared to optimum adhesive mass (1g vs 0.5g, $p<0.05$).

Based on the results in Figure 6 and Table 4, the null hypothesis, that the use of adhesives will make no significant difference to the force required to displace the mandibular free end saddle from the ridge, can be rejected for all adhesives. The use of adhesives significantly increased the force required to displace the denture ($p<0.001$). The results also demonstrate Fixodent neutral taste demonstrated the highest retention ($p<0.01$), followed by Polygrip® products and finally Boots Smile. There was no significant difference between both Polygrip® products due to similar compositions, even though the products are marketed for different applications. Both Polygrip products had significantly higher retention forces when compared to Boots Smile ($p<0.05$).

Figures 7 to 9 show the results from the finite element model analysis. The distal portion of the saddle required the least amount of load to create a 1mm vertical displacement at the loading position due to the creation of moments about the fulcrum (FEA model = 1.98N and experimentally = 1.87±0.55 N). The force required to induce a 1mm vertical displacement was found to have an inverse linear relationship as the distance from the fulcrum increased. The finite element analysis data correlated well with the experimental data closely demonstrating moments about the fulcrum to be a major contributing factor in denture displacement. By positioning the load along the saddle closer to the fulcrum, up to 77% more force is required to displace the denture vertically 1mm at the position of the load. Therefore the null hypothesis, that the force to cause denture displacement will not significantly vary as the position of load is altered along the saddle length, can be rejected. These results also confirm that the mid-value of displacement force will be reached at the mid-point of the saddle. This retrospectively means that the mid-point of the saddle is the ideal position to obtain median values of retention for practical experiments.

Discussion

Although removable partial dentures enhance patient quality of life and have several advantages (generally less expensive, minimal tooth preparation, longer edentulous spans can be restored and replacement of missing alveolar ridge tissues is possible) there are several limitations to their use (clasps being unattractive, designs being bulky/complicated and gagging issues) [25]. There is also some evidence to suggest that removable partial dentures cause an increase in caries and periodontal destruction [26, 27], although it is possible to reduce this damage to negligible levels with careful denture design and good oral hygiene [28, 29]. The major limiting factors for removable partial dentures and the highest causes for patient dissatisfaction are poor retention and instability [9]. This study therefore investigated the potential for denture adhesive to enhance retention of partial removable dentures, in particular mandibular free end saddle partial dentures.

The use of adhesive was found to enhance the retention of the mandibular free end saddle partial denture and altering the volume was also found to have a significant effect on retention forces. The amount will vary depending on the saddle area and large volumes of adhesive may not be well tolerated by patients; however it may still be worth informing patients that variations in the amount of adhesive used can potentially result in significantly large increases in retention (e.g. 0.2g = 4.41±0.28N, 0.6g = 6.66±0.68N). An assumption was made however in this study that the optimum amount will be broadly similar for all of the adhesives in the experiment because they are all gel based and, therefore, achieve retention through very similar mechanisms. Further studies using a variety of adhesives on different denture designs must be performed to ensure the difference is

significant and likely to have a clinical impact. Nevertheless, it may still be worth encouraging patients who are struggling with retention to try other formulations or consider varying the amount of adhesive used for optimum results, bearing in mind that excessive adhesive can also lead to poorer retention.

The results have clearly demonstrated that the use of adhesive significantly increases the force required to displace mandibular free end saddle partial dentures by a minimum of nine-fold compared with the control without adhesive. Fixodent neutral taste increased the retention by twenty three-fold. Interestingly, the greater success of Fixodent in retaining dentures correlates with other *in vitro* studies [6, 30] and qualitative *in vivo* studies [31]. This may be attributed to its composition, which includes silica, a component that may alter the viscosity of the gel and reduce moisture, ultimately increasing frictional forces between the saddle and the mucosa. Correlating the retention forces obtained in this study with the viscoelastic properties of the adhesives may yield useful information on this theory and develop potential methods of improving denture adhesive formulations. Fixodent however contains zinc, which in light of recent health concerns [32, 33] perhaps should be used in smaller quantities. It is therefore not recommended for patients to use excessive amounts of zinc containing Fixodent neutral taste in an attempt to reproduce the results of this study due to potential for elevated serum levels of zinc, which may result in hypocupremia and neurologic diseases [34]. Although Fixodent yielded the highest mean level of retention it may not perform *in vivo* when used in the limited amount recommended to avoid the potentially harmful side effects of zinc. It is vital to consider such factors when selecting and optimising adhesive volumes for maximum retention. Certain denture adhesives also have several disadvantages associated with them [35]. Insoluble adhesives, such as denture pads, can cause tissue destruction; extended use of certain adhesives have been associated with cytotoxicity and irritation; denture adhesives have been found to contain fungal and bacterial contaminants or even support growth of certain oral pathogens (this is an issue particularly for immunocompromised patients); patient misuse can have adverse health effects; and patients have reported the use of adhesives to cause difficulties in cleaning the denture [35]. This study purely focused on achieving the optimum retention, which involved using a large amount of adhesive. These amounts may not be well tolerated by all patients but, at least with the zinc-free products tested, the results can potentially be reproduced *in vivo*.

The finite element model demonstrated a large increase in force required to induce a vertical 1mm displacement of the denture when loaded in the mesial end when compared to the distal end (up to 77% greater). It is worth noting however that a 1mm displacement at the mesial end of the saddle would create a displacement larger than 1mm at the distal end due to the fulcrum acting as a hinge. Similarly a 1mm displacement at the distal end would result in a displacement of less than 1mm in the mesial end. This would explain the inverse linear relationship between distance from the fulcrum and force required to displace the denture vertically 1mm. The agreement between the finite element results and the experimental results confirms that the fulcrum acts as a hinge and therefore generates larger moments on the saddle as forces move further away from the fulcrum. This raises an important clinical point when designing mandibular free end saddle partial dentures with no active retention. It is worth limiting the number of teeth present on the saddle to the fewest necessary to meet clinical requirements. Placing additional teeth on the distal portion of the saddle where not clinically necessary creates greater moments about the fulcrum, which during mastication are more likely to induce denture displacement. This design principle is well established [36], but these results now quantify the reduction in force required for denture displacement and therefore further justify this design principle as best practice. One main limitation of the finite element-based data is its inability to model denture adhesives. Nevertheless the retention force values obtained experimentally when employing 0.2g of adhesive correlate well with the finite element results.

In vitro models are a good starting point for most experimental hypotheses because they have a small fraction of the logistical and financial implications of clinical trials and allow for reproducible

results, which can be compared across studies. Although performed in more controlled conditions, data generated by *in vitro* models are difficult to extrapolate to *in vivo* scenarios due to the complexities of biological systems and therefore care must be taken to avoid over-interpretation of results and definitive conclusions on clinical outcomes. The results from *in vitro* models may however generate useful data and aid clinical trials by establishing optimum conditions for known variables. It is therefore essential when designing *in vitro* models and test methods that conditions which accurately and reproducibly replicate *in vivo* environments are considered. Existing test methods use two flat plates, usually acrylic, to test adhesive strength. There is no concept of *in vivo* geometry and how it affects retention. Such limitations may lead to an adhesion value that is not necessarily representative to that which occurs in the oral cavity. In order to accurately test denture adhesives, the free end saddle area and the geometry of the ridge should be reproduced along with the oral mucosa and reflecting tissues. The geometry of the ridge has been accurately modelled in this study using a cast created from a two-stage impression technique. Reproducing the anatomy of the oral mucosa however, represents a significant challenge due its complex physical properties [6]. Softer rubber and silicon materials demonstrate promise; however a biomechanically suitable material has not yet been developed despite work being carried out in this area [37-39]. One uncontrolled variable in this study was the force used when placing the denture on the cast. This variable was minimised by using the same operator and is also representative of the subtle variation in force which patients are likely to exhibit when placing their dentures. This variable was further eliminated by a suitable number of repetitions, in this case 10 per sample group based on the power calculation. It is the author's opinion that different forces would be optimal for different adhesives depending on the viscosity of the adhesive (e.g. excessive force on a lower viscosity adhesive would cause an increased amount to be displaced from the saddle area, therefore potentially leaving a less than optimal amount of adhesive between the saddle and cast).

Nevertheless future work will focus on optimising this model to account for cyclic loading over time, will investigate potentially using artificial saliva, testing at an appropriate body temperature and testing a range of adhesive types (e.g. powders and strips). The model must also be further refined to encompass a range of different denture locations and likely clinical scenarios. This *in vitro* model was designed to mimic the worst-case clinical scenario in order to produce an estimate of the percentage improvement in retention that can be expected by the worst affected patients. A bilateral free end saddle case would in theory be less stable and exhibit less retention than a unilateral saddle. The difference is likely to be minimal however, when the initial level of retention is as low as is the case with the patient chosen for this study, any additional improvement in retention can still be beneficial to the patient's quality of life.

Conclusion

A more clinically accurate *in vitro* model was developed in this study, which demonstrated the use of denture adhesives to significantly increase the retention of mandibular free end saddle partial dentures. The model demonstrated that mass of adhesive played a significant role in denture retention and there are significant differences between the performances of different commercially available adhesive formulations. The results of the finite element analysis model showed that the 77% more force is required to vertically displace the mandibular free end saddle denture when the loading is applied at the mesial side

of the saddle area when compared to the distal end. This result provides evidence to support limiting the number of teeth on free end saddles to the mesial and mid portion of the saddle to reduce moments about the fulcrum and therefore the likelihood of displacement. These results may better inform clinicians on best practice and may be beneficial to patients experiencing movement of mandibular free end saddle dentures.

Conflicts of interest: none

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References

1. Darvell BW, Clark RKF. Prosthetics: The physical mechanisms of complete denture retention. British Dental Journal 2000;189:248-252
2. Yankell SL. Overview of research and literature on denture adhesives. Compendium of Continuing Education in Dentistry 1984;Suppl 4:S18-21
3. Karlsson S, Swartz B. Denture adhesives - their effect on the mobility of full upper dentures during chewing. A cineradiographic study. Swedish Dental Journal 1981;5(5-6):207-11
4. Ghani F, Picton DC. Some clinical investigations on retention forces of maxillary complete dentures with the use of denture fixatives. Journal of Oral Rehabilitation 1994;21(6):631-40
5. DeFurio A, Gehl DH. Clinical study of the retention of maxillary complete dentures with different base materials. Journal of Prosthetic Dentistry 1970;23(4):374-80
6. Johnson A, Al-Kaisy N, Miller CA, et al. The effect of denture design and fixatives on the retention of mandibular complete dentures tested on a novel *in-vitro* edentulous model. European Journal of Prosthodontics & Restorative Dentistry 2013;21(2):64-74

7. Steele J, O'Sullivan I. Adult Dental Health Survey 2009: The NHS Information Centre for Health and Social Care, 2011.
8. Wagner B, Kern M. Clinical evaluation of removable partial dentures 10 years after insertion: success rates, hygienic problems, and technical failures. Clinical Oral Investigations 2000;4(2):74-80
9. Bilhan H, Erdogan O, Ergin S, Celik M, Ates G, Geckili O. Complication rates and patient satisfaction with removable dentures. J Adv Prosthodont 2012;4(2):109–115
10. Cooper LF. The current and future treatment of edentulism. Journal of Prosthodontics 2009;18(2):116-22
11. Fenlon MR, Sherriff M. An investigation of factors influencing patients' satisfaction with new complete dentures using structural equation modelling. Journal of Dentistry 2008;36(6):427-34
12. Fish SF. Partial dentures. 6. Free-end saddle dentures. British Dental Journal 1970;128(10):495-502
13. Allen PF. How long should a shortened dental arch be? [Reprint in SADJ. 2009 Sep;64(8):344-6; PMID: 20034287]. Dental Update 2008;35(7):454-6, 59
14. Kumar AB, Walmsley AD. Treatment options for the free end saddle. Dental Update 2011;38(6):382-4, 87-8
15. Carr AB, McGivney GP, Brown DT. McCraken's Removable Partial Prosthodontics. 11th ed. China: Elsevier Mosby, 2005
16. Witter DJ, Van Elteren P, Kayser AF, et al. Oral comfort in shortened dental arches. Journal of Oral Rehabilitation 1990;17(2):137-43
17. Stafford GD. Denture adhesives--a review of their uses and compositions. Dental Practitioner & Dental Record 1970;21(1):17-9

18. Munoz CA, Gendreau L, Shanga G, et al. A clinical study to evaluate denture adhesive use in well-fitting dentures. Journal of Prosthodontics 2012;21(2):123-9

19. Zarb GA, Bolender CL, Eckert SE. Prosthodontic treatment for edentulous patients : complete dentures and implant-supported prostheses. 12th ed. ed: St. Louis : Mosby, 2004.

20. Sarnat AE. The efficiency of cobalt samarium (Co5Sm) magnets as retention units for overdentures. Journal of Dentistry 1983;11(4):324-33

21. Chung KH, Chung CY, Cagna DR, et al. Retention characteristics of attachment systems for implant overdentures. Journal of Prosthodontics 2004;13(4):221-6

22. Rutkunas V, Mitzutani H. Retentive and Stabilizing Properties of Stud and Magnetic Attachments Retaining Mandibular Overdenture. An *in Vitro* Study. Stomatologija, Baltic Dental and Maxillofacial Journal 2004;6(3):85-90

23. Rutkunas V, Mizutani H, Takahashi H. Influence of attachment wear on retention of mandibular overdenture. Journal of Oral Rehabilitation 2007;34(1):41-51

24. Kumar MS, Thombare RU. A Comparative Analysis of the Effect of Various Denture Adhesives Available in Market on the Retentive Ability of the Maxillary Denture: An *In Vivo* Study. J Indian Prosthodont Soc 2011;11(2):82–88

25. McCord F, Smales R. Oral diagnosis and treatment planning: part 7. Treatment planning for missing teeth. British Dental Journal 2012;213:341 - 351

26. MacEntee MI. Biologic sequelae of tooth replacement with removable partial dentures: a case for caution. Journal of Prosthetic Dentistry 1993;70(2):132-4

27. Jepson NJ, Moynihan PJ, Kelly PJ, et al. Caries incidence following restoration of shortened lower dental arches in a randomized controlled trial. British Dental Journal 2001;191(3):140-4

28. Bergman B, Hugoson A, Olsson CO. Caries, periodontal and prosthetic findings in patients with removable partial dentures: a ten-year longitudinal study. Journal of Prosthetic Dentistry 1982;48(5):506-14

29. Bergman B, Ericson G. Cross-sectional study of the periodontal status of removable partial denture patients. Journal of Prosthetic Dentistry 1989;61(2):208-11

30. Kore DR, Kattadiyil MT, Hall DB, Bahjri KB. *In vitro* comparison of the tensile bond strength of denture adhesives on denture bases. Journal of Prosthetic Dentistry 2013;110(6): 488–93.

31. Kelsey CC, Lang BR, Wang RF. Examining patients' responses about the effectiveness of five denture adhesive pastes. J Am Dent Assoc 1997;128(11):1532-8

32. Doherty K, Connor M, Cruickshank R. Zinc-containing denture adhesive: a potential source of excess zinc resulting in copper deficiency myelopathy. British Dental Journal 2011;210(11):523-5

33. Nations SP, Boyer PJ, Love LA, Burritt MF, Butz JA, Wolfe GI, Hynan LS, Reisch J, Trivedi JR. Denture cream: An unusual source of excess zinc, leading to hypocupremia and neurologic disease. Neurology 2008;71(9):639-643

34. Tezvergil-Mutluay A, Carvalho RM, Pashley DH. Hyperzincemia from ingestion of denture adhesives. Journal of Prosthetic Dentistry 2010;103(6):380-3

35. Duqum I, Powers KA, Cooper L, Felton D. Denture adhesive use in complete dentures: clinical recommendations and review of the literature. General Dentistry 2012;60(6):467-77

36. Tyson KW, Yemm R, Scott BJJ. Understanding partial denture design. 1st Edition ed: Oxford : Oxford University Press, 2007

37. Kydd WL, Daly CH. The biologic and mechanical effects of stress on oral mucosa. Journal of Prosthetic Dentistry 1982;47(3):317-29

38. Kydd WL, Daly CH, Wheeler JB, 3rd. The thickness measurement of masticatory mucosa *in vivo*. International Dental Journal 1971;21(4):430-41

39. Kydd WL, Mandley J. The stiffness of palatal mucoperiosteum. Journal of Prosthetic Dentistry 1967;18(2):116-21

Figure Caption

Figures

Figure 1: Baseplate with displacement loop for loading at the mid-point of the saddle.

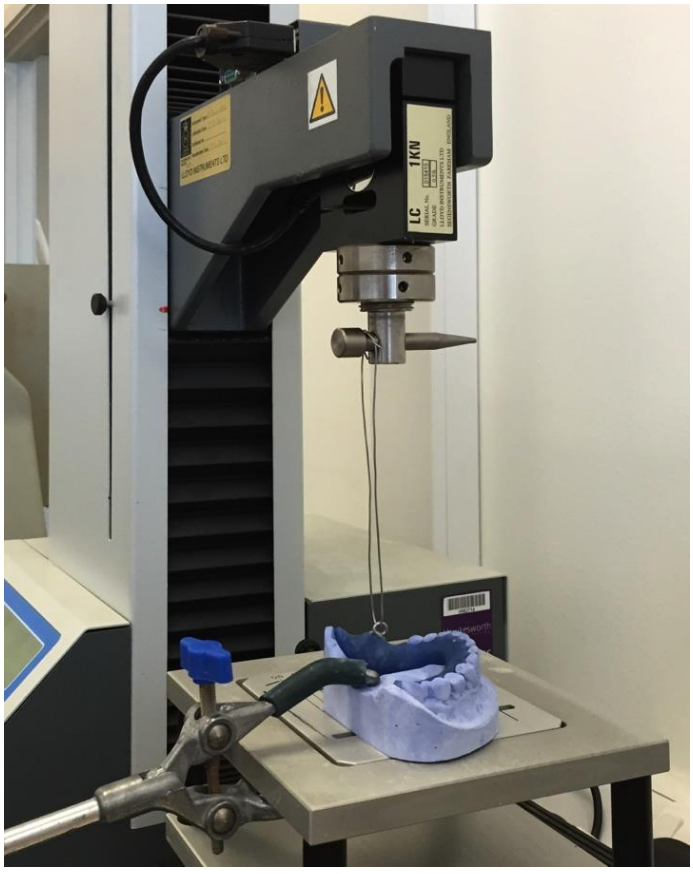


Figure 2: Experimental setup of the baseplate and cast on a Lloyd LF-Plus materials testing machine.

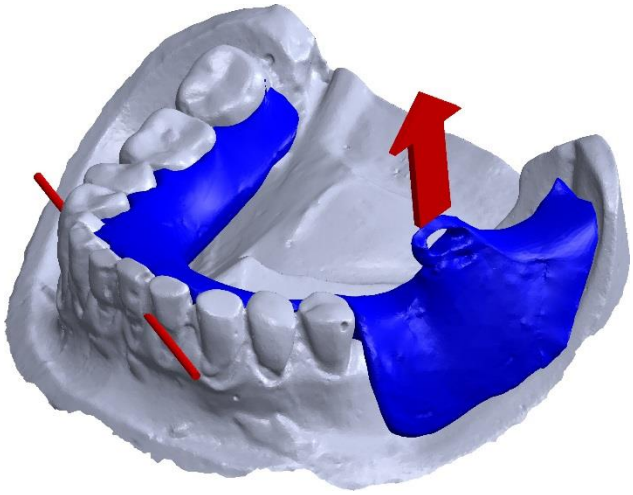


Figure 3: 3D CAD model indicating the position of the fulcrum against the anterior teeth when the vertical force is applied to the saddle area.

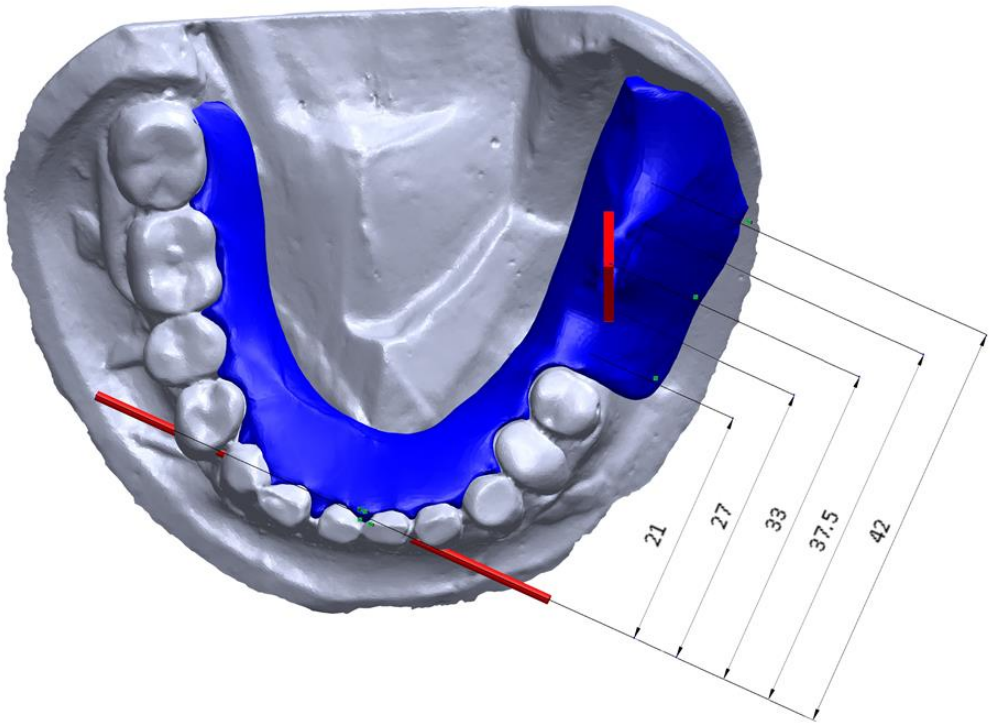


Figure 4: 3D CAD model showing the distances between the fulcrum and the loading points at the mesial and distal ends of the saddle.

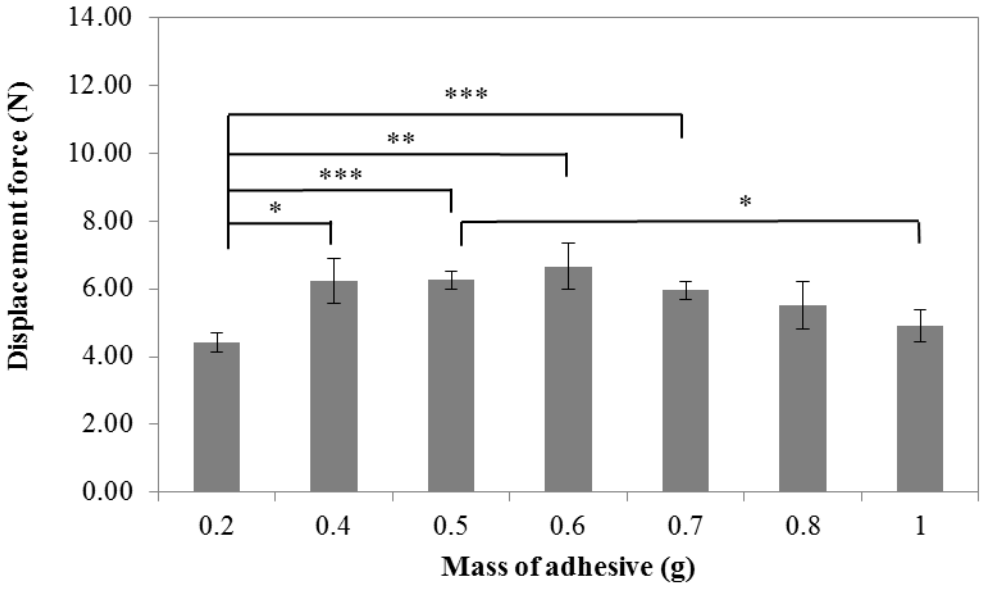


Figure 5: The effect of varying the mass of Polygrip® denture adhesive on displacement force (error bars represent standard error for n=10, * - $p<0.05$, ** - $p<0.01$, *** - $p<0.001$).

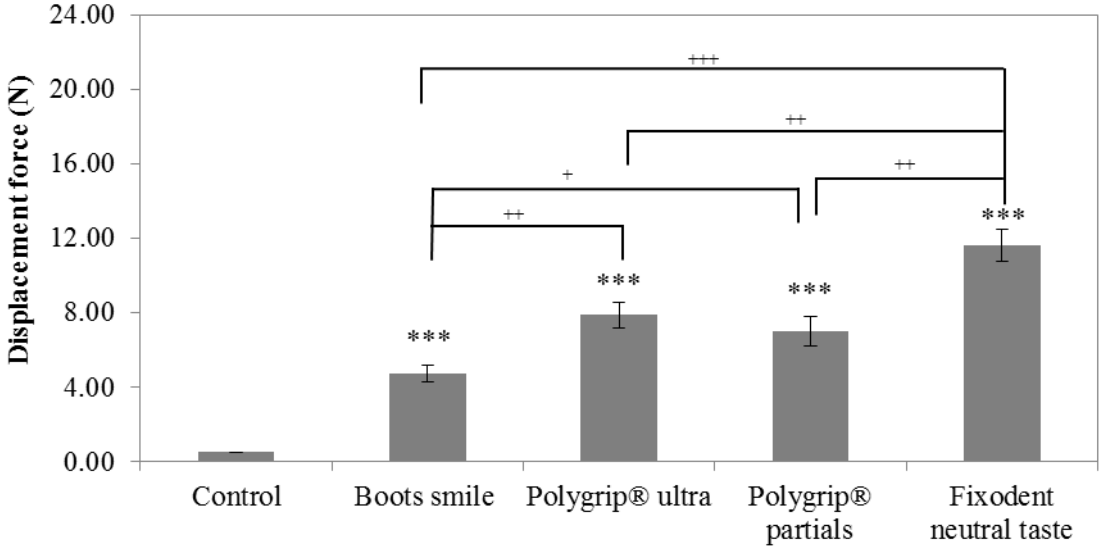
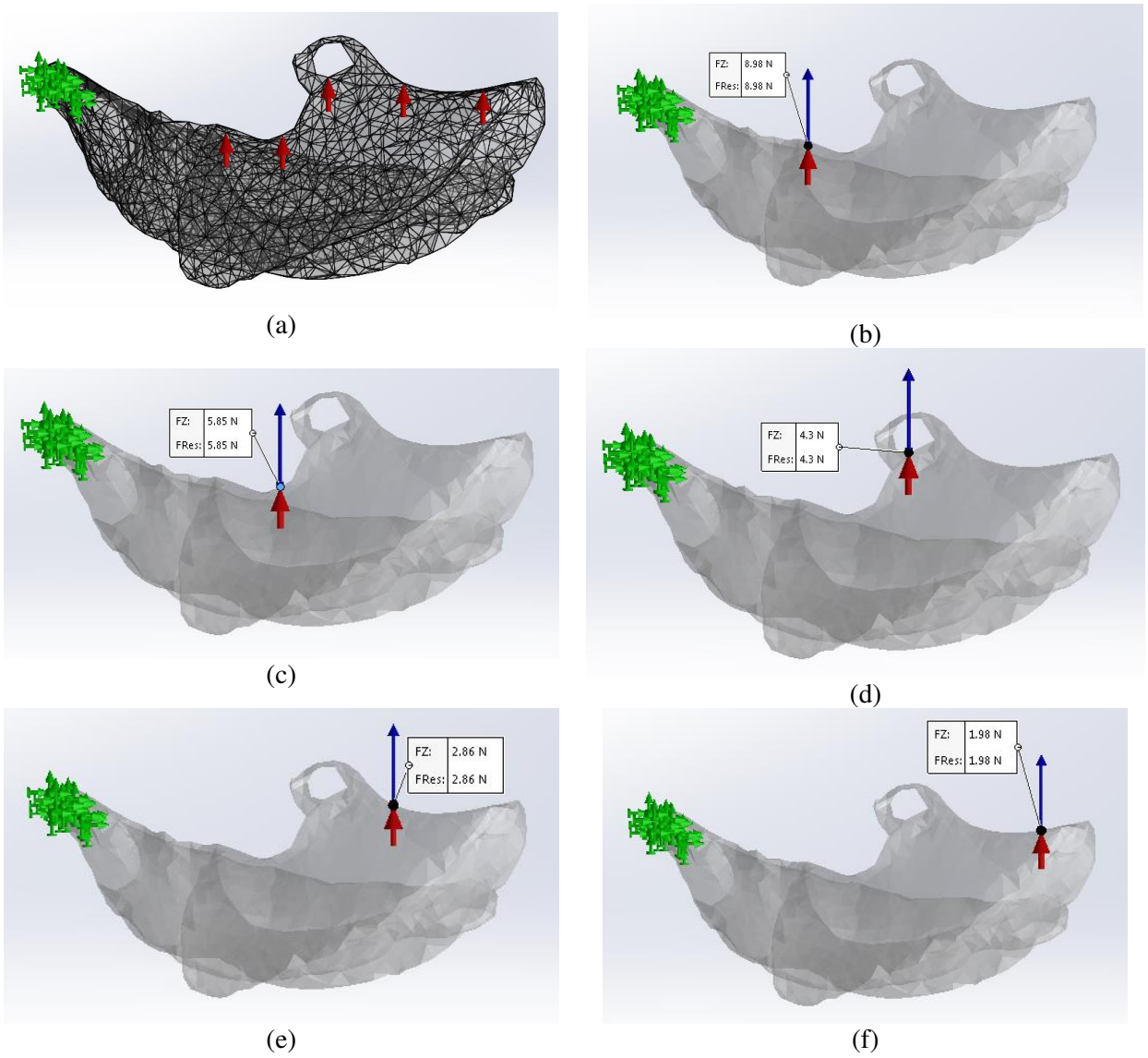


Figure 6: Displacement force of the control and four adhesive experimental groups when tested using the *in vitro* model (error bars represent standard error for n=10, *** - significantly different to control $p<0.001$, +++ - $p<0.001$).



(a) (b) (c) (d) (e) (f)

Figure 7: Side view of the finite element modelling results demonstrating the loads required to displace the denture vertically 1mm as the distance along the saddle perpendicular to the fulcrum increases. (a) Mesh applied to the model, fixtures along fulcrum (green) and displacement points (red arrows); 1mm displacements at (b) 21mm, (c) 27mm, (d) 35mm, (e) 37.5mm and (f) 42mm from fulcrum.

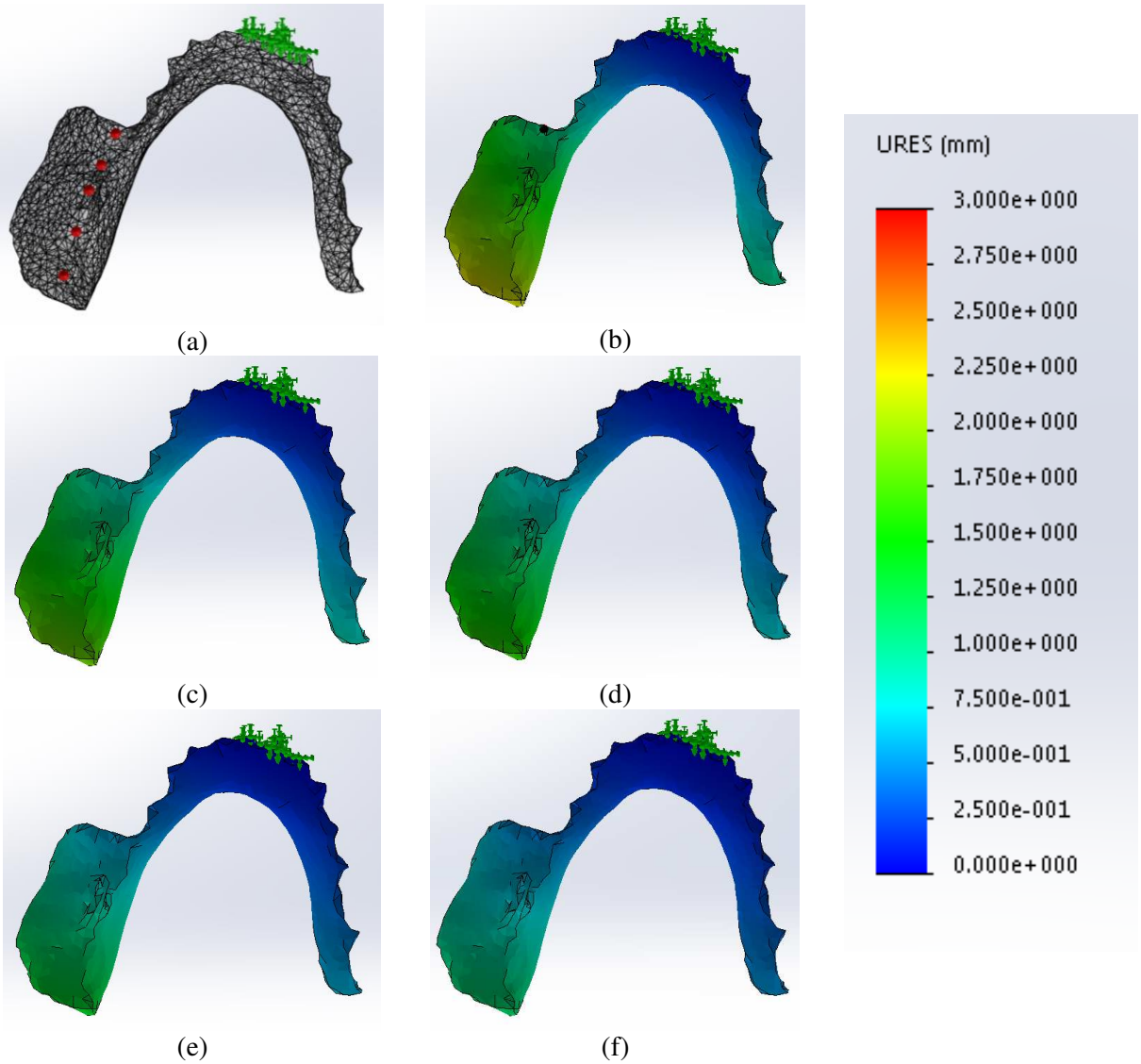


Figure 8: Displacement plots from the finite element modelling analysis. (a) Mesh applied to the model, fixtures along fulcrum (green) and displacement points (red arrows); 1mm displacements at (b) 21mm, (c) 27mm, (d) 35mm, (e) 37.5mm and (f) 42mm from fulcrum.

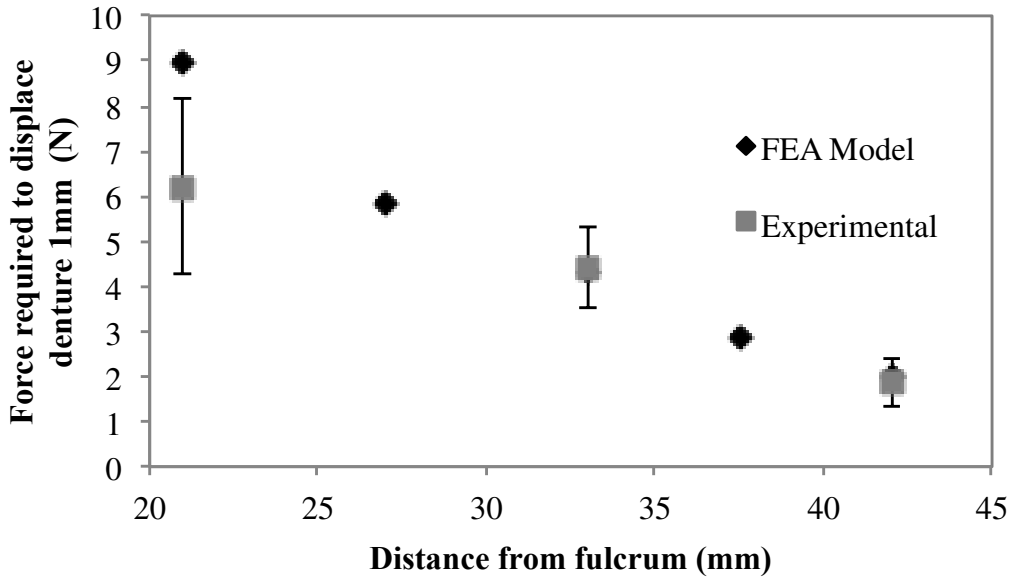


Figure 9: FEA model and experimental results demonstrating the maximum force required to displace the denture 1mm as the distance from the fulcrum increases (error bars represent experimental standard deviation from 10 samples).

Figure captions

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Tables

Table 1: Composition and details of adhesives tested.

Adhesive name	Consistency	Manufacturer	Ingredients
Polygrip® for Partials	Paste	GlaxoSmithKline, Stafford Miller Ltd, Dungarvan Co. Waterford, Ireland)	Calcium/Sodium, PVM/MA copolymer, Petrolatum, Cellulose Gum, Paraffinum, Liquidum,
Polygrip® Ultra	Paste	GlaxoSmithKline, Stafford Miller Ltd, Dungarvan Co. Waterford, Ireland)	Calcium/Sodium, PVM/MA copolymer, Petrolatum, Cellulose Gum, Paraffinum, Liquidum, Aroma, Cl 45430
Fixodent Neutral Taste	Paste	Procter and Gamble UK, Weybridge, Surrey, KT13 OXP	Calcium/Zinc, PVM/MA copolymer Petrolatum, Cellulose Gum, Paraffinum, Liquidum, Silica
Boots Smile	Paste	The Boots company PLC Nottingham England NC2 3AA	Calcium/ sodium, PVM/MA copolymer, liquid paraffin, white soft paraffin, cellulose gum, purified water, Flavour, Bisabolol, BHT, Cl 73360

Table 2: Material properties assigned to the finite element denture model.

Elastic Modulus	3 GPa
Poisson's Ratio	0.35
Shear Modulus	890 MPa
Mass Density	1200 kg/m^3
Tensile Strength	73 MPa
Yield Strength	45 MPa
Thermal Expansion Coefficient	5.2e-005 K^{-1}
Thermal Conductivity	0.21 W/mK
Specific Heat	1500 J/kgK

Table 3: Results of the statistical analysis (two-sample T-test assuming equal variances) to assess statistical significance between the displacement force as a result of adhesive mass.

	0.2g	**0.4g**	**0.5g**	**0.6g**	**0.7g**	**0.8g**	**1.0g**
0.2g	-	-	-	-	-	-	-
0.4g	0.019	-	-	-	-	-	-
0.5g	0.000	0.994	-	-	-	-	-
0.6g	0.006	0.668	0.583	-	-	-	-
0.7g	0.000	0.683	0.429	0.345	-	-	-
0.8g	0.162	0.458	0.339	0.258	0.568	-	-
1.0g	0.367	0.367	0.022	0.048	0.068	0.485	-

Table 4: Results of the statistical analysis (two-sample T-test assuming equal variances) to assess statistical significance between different commercially available adhesives.

	Control	**Boots smile**	**Polygrip® ultra**	**Polygrip® partials**	**Fixodent neutral taste**
Control	-	-	-	-	-
Boots smile	0.000	-	-	-	-
Polygrip® ultra	0.000	0.001	-	-	-
Polygrip® partials	0.000	0.026	0.411	-	-
Fixodent neutral taste	0.000	0.000	0.004	0.001	-