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Review

Denture–Mucosa Pressure Distribution and Pressure–Pain Threshold in In Vivo, In Vitro and In Silico Studies: A Literature Review

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Abstract: Aims. The purpose of this systematic review was to evaluate studies that assessed denture–mucosa pressure distribution and pressure–pain threshold and their methodology, used to measure such pressure distributions, mainly in complete and implant overdentures. Materials and methods. An electronic search of the relevant full-text peer-reviewed literature on denture–mucosa pressure distribution was done. Searches were performed independently by two researchers by using the OVID Medline, PubMed and Web of Science databases from 1 January 1946 to 31 December 2021 using the following MeSH terms; (denture OR complete dentures OR implant supported dentures) AND (mucosa OR mucous membrane) AND (pressure OR hydrostatic pressure). Only those publications in the English language were included. Furthermore, a manual search of the citations of the included studies was done to ensure a thorough search was conducted. Results. A full text review resulted in a total of eighteen studies. Of these, seven evaluated various intraoral pressures, two investigated the pressure–pain threshold in edentulous oral mucosa, five measured intraoral pressure through finite element analysis/FEA studies, two demonstrated pressure transducer and pressure measuring systems, and two investigated the comparison between implant-overdentures and complete dentures. Conclusions. To date, there is no study that assesses the pressure distribution on oral mucosa to provide a standardised and validated baseline pressure range which can be used to improve the designs and materials used for fabricating complete dentures. The relationship between pressure on the oral mucosa and the pain threshold of denture-wearing patients still remains poorly understood. There is yet no baseline data which can be universally applied for future studies; to correlate the oral mucosa pressure and pain threshold of edentulous patients encourages further research, especially comparing mucosa pressure under different denture designs for both complete and implant overdentures.

Keywords: pressure; oral mucosa; edentulous; complete dentures; implant overdentures

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1. Introduction

It has been well established that some edentulous patients experience psychosocial and functional complications [1,2] which can adversely affect the patient's quality of life. This is a significant global problem as the prevalence of edentulism remains as the worldwide demographic transitions into an ageing population, which is most commonly evident in industrialised countries. The World Health Organisation (WHO) reported that by 2050 [3], approximately 22% of the population would be in the age group of 60 years and above. Consequently, an exponential demand for ongoing oral health care would be expected to improve, maintain and promote the oral health of this ageing population.

Complete dentures, implant overdentures and partial dentures are often fabricated to restore the aesthetic and functional demands of edentulous patients. As the various prostheses rely on the support from the oral mucosa and residual ridges, it is critical to minimise any excessive residual ridge resorption [4] by evenly distributing occlusal loads [5]. As the oral mucosa of an edentulous arch is comprised of mainly epithelial and connective tissue [6], the histological reaction to wearing dentures is notably significant in the mechanical and physiological capacity of the mucosa. This also relates to patients' denture-wearing experience as any excessive localised pressure can lead to pain or discomfort [4], leading to unnecessary soft and hard tissue damage affecting the masticatory function, nutritional intake and overall oral health-related quality of life.

In the absence of natural teeth, mechanoreceptive function [7] and proprioception occur through continuous stimulation between the denture base and oral mucosa. Therefore, patterns of intraoral pressures within the oral cavity depend on whether it is acceptable functional behaviours, such as mastication, swallowing and speech, or parafunctional behaviours, such as bruxism [8]. Management of the amount and pattern of pressure exerted on oral mucosa is an important aspect for denture treatment, to minimise any excessive residual ridge resorption impacting on the stability and retention of removable prostheses. As the capacity of the oral mucosa under continuous loading is variable [9] and dependent on the level and duration of the mechanical load during denture wearing, there is limited knowledge on the physiological parameters for the oral mucosa's pain threshold. Notably, the pressure–pain threshold (PPT), is a major area of interest within denture treatment as it is the maximum pressure before pain is experienced by the patient [6,7].

Previous studies have reported on the maximum ability that the edentulous mucosa can bear when subjected to masticatory stress [8,9]. However, as the local variability of the relationship between pressure on the mucosa and the poor ability of methods to report this local variability, which depend also on mucosa properties at this specific site, the pain threshold of denture-wearing patients still remains poorly understood. Although various findings correlating hydrostatic pressure to soft-tissue induced bone resorption have been investigated [8,9], there are still some uncertainties about the mechanical and physiological capacity of the oral mucosa. Consequently, there is a need for such reviews in order to understand the correlation between the denture–mucosa pressure distribution, PPT and how this affects the patient's oral health-related quality of life.

Therefore, the purpose of this systematic review was to gather the quantitative evidence that assessed the denture–mucosa pressure distribution using conventional complete dentures or implant overdentures and how this correlated to the pressure–pain threshold. Furthermore, the secondary aim was to evaluate the methodologies used to measure such pressure distributions.

2. Materials and Methods

An electronic search using Ovid MEDLINE, PubMed and Web of Science was performed with the following MESH (Medical Subject Headings) terms: (denture OR complete dentures OR implant supported dentures) AND (mucosa OR mucous membrane) AND (pressure OR hydrostatic pressure). The overall search strategy is presented in Table 1. The evaluation criteria were defined in accordance with the PICO(S) (Patient or Population, Intervention, Control or Comparison, Outcome and Study types) criteria. The review included all studies involving completely edentulous patients with conventional complete dentures, or implant overdentures. There were no restrictions regarding the sex or age of the participants. The selection inclusion criteria included publications in English language only. Studies using in vitro and in silico methods were also included. Studies with animal models, studies irrelevant to the focus question, those where only the abstracts were available, as well as reviews were excluded from the selection. Full-text articles were included to ensure thorough review of the respective studies. This was completed to identify any gaps within the current literature to supplement the development of our methodology to measure the denture–mucosa pressure distribution in a typical edentulous patient. Outcome parameters were defined with respect to existing reviews; the main outcome parameters of the included studies according to the denture–mucosa pressure distribution in terms of PPT, as well as an evaluation of the methodology used to measure pressure, including the standardisation and validity of the results. The lower limit on the publication date was 1 January 1946 and the search included up to 31 December 2021. Titles and abstracts of potential studies were assessed independently by two reviewers (AP, JJEC) according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. Studies that met the inclusion and exclusion criteria were evaluated for its relevance for the purpose of the current systematic review. A further manual search was also conducted using the citations of the included studies. Furthermore, the two reviewers evaluated the full-text studies independently and cross-referenced the individually selected literature to reduce the risk of bias of each included study. Inter-rater reliability was evaluated using SPSS ver 26. (IBM) using Cohen's Kappa Coefficient.

Table 1. Systematic search strategy.

Focus question: In patients wearing removable dental prostheses, what is the difference in mucosal pressure between conventional complete dentures in comparison to implant supported overdentures? What are the methodologies used to measure the denture pressure distributions?	
Search strategy	
Population	Completely edentulous patients
Intervention (or exposure)	Complete dentures
Comparison	Implant supported dentures
Outcome	Denture–mucosa pressure distribution, pressure–pain threshold
Search combination	Denture OR complete dentures OR implant supported dentures AND Mucosa OR mucous membrane AND Pressure OR hydrostatic pressure
Database search	
Electronic database searched	Ovid MEDLINE PubMed Web of Science
Selection inclusion criteria	English language Full-text only In vivo studies In vitro studies In silico studies
Selection exclusion criteria	Studies in languages other than English Studies with animal models Studies irrelevant to the focus question Abstracts only Reviews

3. Results

The search strategy details are illustrated in a PRISMA flow chart in Figure 1. The systematic database searches led to a total of 76 abstracts initially. According to the exclusion criteria, 59 studies were excluded due to being review articles, conference proceeding abstracts and being not relevant to the topic. Thus a total of 17 selected articles were included in the final analysis. Six articles were further identified to be relevant via a manual search. During the full-text screening, five articles were excluded since they were out of the scope for this systematic review, being clinical studies conducted with dentate patients. Thus, a total of 18 studies [4,5,5,7–21] met the inclusion and exclusion criteria to be included in the final analysis (Table 2. A strong inter-examiner agreement was found during the full-text screening and article final selection (Cohen's Kappa, 0.95). All 18 eligible studies were either in vivo studies (12 articles) and in vitro/in silico studies (8 articles) that were well-designed and found to have a low risk of bias for most criteria, except for the participant selection bias for mainly in vivo studies. For most studies, the risk of bias assessment (Table 2), especially for participant selection was difficult to identify due to the lack of information provided regarding the participant selection process (identified as "unclear").

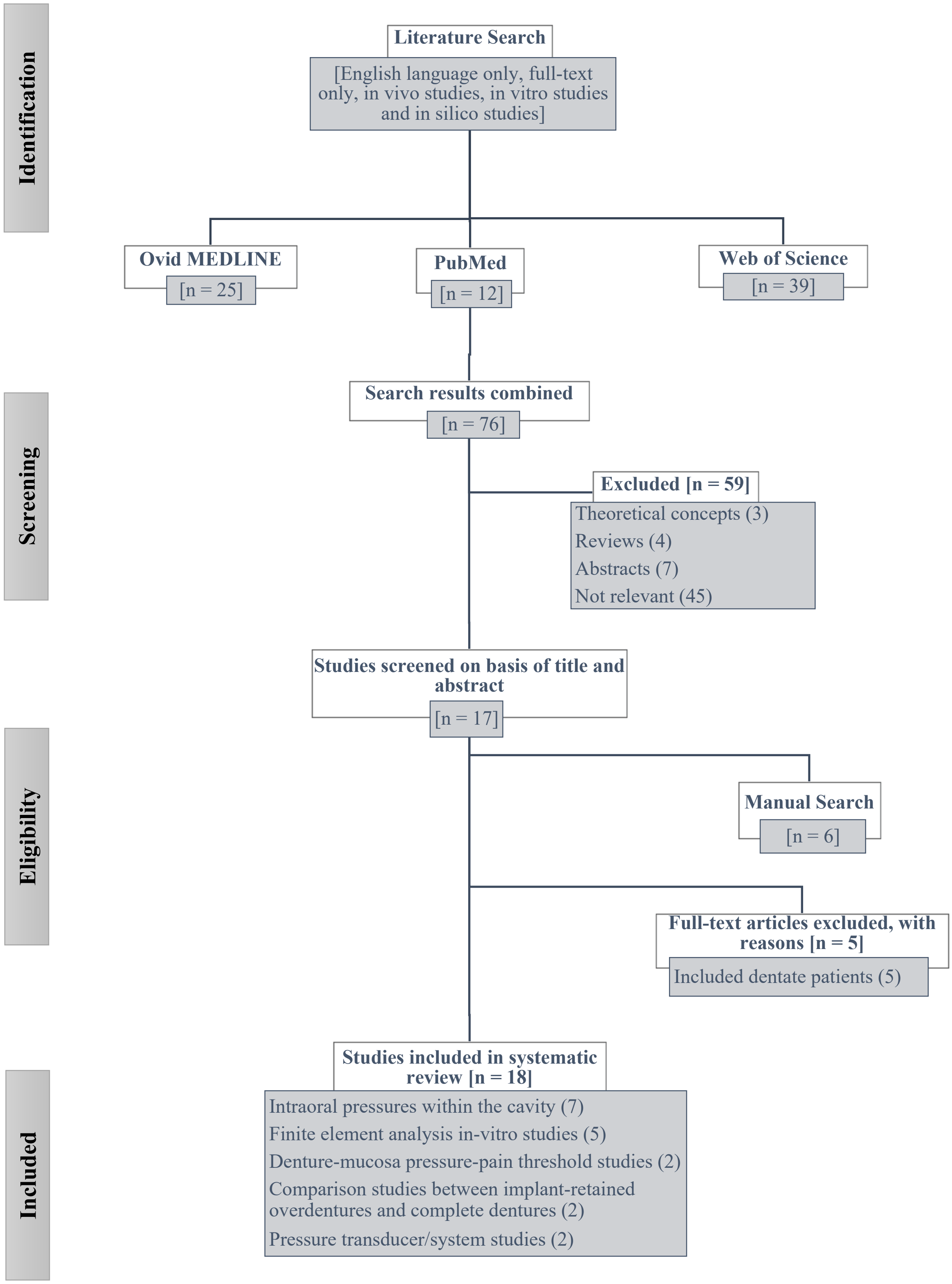

Figure 1. Flowchart of the systematic literature search.

Table 2. Risk of bias summary.

Study (Year)	Random Sequence Generation (Selection Bias)	Allocation Concealment (Selection Bias)	Blinding of Participants and Personnel (Performance Bias)	Blinding of Outcome Assessment (Detection Bias)	Incomplete Outcome Data (Detection Bias)	Selective Reporting (Reporting Bias)	Other Bias
Ahmad et al. (2015)	✖	✖	?	?	✔	✔	✔
Assunção et al. (2009)	✖	?	✔	✔	✔	✔	✔
Avci & Aslan (1991)	?	?	✔	✔	✔	✔	✔
Berg et al. (1967)	?	?	✔	✔	✔	✔	✔
Chen et al. (2015)	✖	?	✔	✔	✔	✔	✔
Chen et al. (2016)	✖	?	✔	✔	✔	✔	✔
Cutright et al. (1976)	?	?	✖	✖	✔	?	✔
Józefowicz (1972)	?	?	?	✔	✔	✔	✔
Kubo et al. (2009)	✖	✖	?	✖	✔	✔	✔
Ogawa et al. (2004)	✖	?	?	✖	✔	✔	✔
Roedema (1976)	✖	✖	?	✖	✔	✔	✔
Sato et al. (2019)	?	?	?	✔	✔	✔	✔
Shi et al. (1998)	?	?	?	✖	✔	✔	✔
Tanaka et al. (2004)	✖	?	?	✖	✔	✔	✔
Watson & Abdul (1984)	✖	✖	?	✖	✔	✔	✔
Watson & Huggett (1987)	✖	?	?	✖	✔	?	✔
Źmudzki et al. (2012)	?	?	?	✔	✔	✔	✔
Źmudzki et al. (2018)	✖	✖	?	✔	✔	✔	✔

Key: ✔ (low risk), ✖ (high risk—consider risk of material bias, not any bias), ? (unclear—not enough information to make a clear judgement).

The purpose, methods (type of studies) and pressure range results of all 18 studies included in the final analysis are summarised in Table 3. Due to the different pressure units used in each study, the last column in Table 3 presents the data in a standardised unit, such as kPa, for an easier comparison.

Table 3. Summary of full-text literature review.

Study (Year)	Purpose	Method	Pressure Range	Standardised Unit
Ahmad et al. (2015)	To investigate and compare the residual ridge resorption (RRR) induced by an implant-retained overdenture (IRO) and associative biomechanics and by a conventional complete denture (CD) without implants.	In vivo	Presented as a diagram—unable to interpret.	-23.32 ± 0.81–-34.53 ± 8.07 kPa
Assunção et al. (2009)	To evaluate the effect of different mucosa thicknesses and resiliency on the stress distribution of complete dentures and implant-retained overdentures using a two-dimensional finite element analysis.	In vitro	Presented as a diagram—unable to interpret.	Unable to standardise results
Avci & Aslan (1991)	To present a "closed" hydraulic pressure measuring system capable of measuring pressures at the denture base–mucosal surface interface (to measure the swallowing pressures of edentulous patients for various occlusal vertical dimensions).	In vivo	n/a	n/a

Table 3. *Cont.*

Study (Year)	Purpose	Method	Pressure Range	Standardised Unit
Berg et al. (1967)	To observe and define the relationships between pressures involved in denture-bearing tissue compressibility, vascular bed embarrassment, comfort threshold, adaptation of denture impression materials, and the physiological qualities of the completed prosthetic appliance, which include functional contact with edentulous ridges.	In vivo	30–100 mm Hg	3.99–13.3 kPa (3sf)
Chen et al. (2015)	To evaluate the differences in mucosal hydrostatic pressure of these three different (namely, complete, two and four implant-retained) denture treatments in a patient-specific setting.	In vitro	Presented as a diagram—unable to interpret.	13.3 ± 0.9–14.3 ± 0.9 kPa
Chen et al. (2016)	To develop an inverse procedure to determine these two biomechanical parameters by utilising in vivo experiment of contact pressure between partial denture and beneath mucosa through nonlinear finite element (FE) analysis and surrogate response surface (RS) modelling technique.	In vitro	Presented as a diagram—unable to interpret.	9–87 kPa
Cutright et al. (1976)	To observe pressure movements (waves) beneath the dentures during various masticatory and non-masticatory activities and the forces exerted against the different tissue sites beneath a denture during masticatory and non-masticatory movement.	In vivo	All pressures given in millimetres of mercury and represent maximum range of forces exerted.	Unable to standardise results
Józefowicz (1972)	To obtain reliable data as to the yielding of the maxillary mucoperiosteum by means of a method which would give comparative results and to explore the influence of denture wearing on the yielding of maxillary mucoperiosteum.	In vivo	Measured in degrees of gum softness and mucoperiosteum yielding.	Unable to standardise results
Kubo et al. (2009)	To develop a system to measure the pressure distribution under the base of a removable partial denture (RPD) and to apply it in vivo.	In vivo	461.6 kPa	461.6 kPa
Ogawa et al. (2004)	To examine regional differences and correlations of PPT in edentulous oral mucosa.	In vivo	Presented as a diagram—unable to interpret.	12.5–58.8 kPa (3sf)
Roedema (1976)	To determine the effect of reducing the occlusal table of a complete denture on masticatory pressures developed between supporting mucosal tissues and the base of the prosthesis.	In vivo	Presented as a graph—unable to interpret.	Unable to standardise results

Table 3. *Cont.*

Study (Year)	Purpose	Method	Pressure Range	Standardised Unit
Sato et al. (2019)	To determine the appropriate attachment and design of a denture base for mandibular implant overdenture (IOD), the oral mucosa pressure caused by mandibular implant overdentures was measured using edentulous jaw models with various attachments.	In vitro	Presented as a graph—unable to interpret.	Unable to standardise results
Shi et al. (1998)	To investigate the maximum ability of the masticatory mucosa under the denture base to bear bite force by measuring the stress-bearing area in patients, testing the maximum bite force in the same complete denture-wearers, and analysing the relationship between the force and the stress-bearing area.	In vivo	77–87 kPa	77–87 kPa
Tanaka et al. (2004)	To investigate the effects of denture wearing and bite force on the pressure–pain threshold (PPT) of edentulous oral mucosa.	In vivo	Presented as a graph—unable to interpret.	0.0282–0.166 kPa (3sf)
Watson & Abdul (1984)	To discuss the development of a simple, inexpensive strain gauge based pressure transducer, for use at the denture base–mucosa surface interface.	In vivo	Measured pressure using total pressure peaks, swallowing pressures, maximum pressure, pressures at maximum bites and number of chews above 50% and 100% of maximum biting pressures.	34–140.6 kPa
Watson & Huggett (1987)	To evaluate pressures produced under complete upper and lower dentures at the denture base–mucosal surface interface.	In vivo	Measured pressure using total, mean and maximum pressure peaks, time and chewing frequency	Unable to standardise results
Źmudzki et al. (2012)	To verify the hypothesis that the lower denture causes remarkable mucous membrane overloading resulting from destabilisation of the denture under oblique mastication forces.	In vitro	The highest stresses under the denture reached 252 kPa. Vertical force of 100 N measured in the lab reached 80 kPa on alveolar slopes at lingual side and 250 kPa at the buccal side. Occlusal vertical force of 50 N on the alveolar process slopes at the working side caused stresses of 21.1–214.1 kPa.	21.1–252 kPa (total range)
Źmudzki et al. (2018)	To determine whether the pressures developed beneath a removable mandibular complete denture during mastication would exceed the average pressure–pain threshold in patients for whom the denture foundation had an acceptable load-bearing capacity.	In vitro	Presented as a diagram—unable to interpret.	Unable to standardise results

The studies were characterised into five categories based on their objectives; firstly, 7 evaluated various intraoral pressures [8–14]. A large range of intraoral pressure was observed between the studies after the results were converted into a standardised unit (kPa), ranging from 3.99 kPa [10] to the highest of 461.6 kPa [12]. Out of these 7 studies, the mean intraoral pressure result of 4 studies [8,11,13,14] were not possible to be converted into kPa due to results presented in an image rather than numerical values.

Two studies investigated the pressure–pain threshold (PPT) in the edentulous oral mucosa [6,7]. Ogawa et al. (2004) [6] evaluated the PPT in 15 patients and reported that different areas of the edentulous oral mucosa have a different PPT which varies depending on intraoral locations. Tanaka et al. (2004) [7] also reported that PPT varies around the areas, with an increase in the pain threshold from the anterior to posterior alveolus in both the maxilla and mandible, but decreased from the anterior palate to the posterior palate. The mid palate showed 200–300% higher PPT than the buccal alveolar mucosa.

Five studies were found to measure intraoral pressure through finite element analysis (FEA) studies (Table 4) [4,5,15–17]. Two studies used three-dimensional FEA methods [5,16], whereas the rest of the studies used either two-dimensional or non-linear FEA methods [4,16,17] to analyse the pressure distribution in oral mucosa. Despite the simulation or modelling technique used, all studies reported a higher pressure distribution in implant overdenture groups than complete denture groups. Avci et al. (2009) [18] and Watson et al. (1984) [19] demonstrated the pressure distribution in the oral mucosa using a hydraulic pressure transducer and strain-gauge pressure measuring systems, respectively. They reported that the area of the lower denture was about half that of the maxillary denture and suggested that pressures could become exceedingly high on the lower denture-bearing mucosa during chewing. Two studies [20,21] specifically investigated the comparison between implant-overdentures and complete dentures' pressure distribution. Ahmad et al. (2015) [20] focused on comparing the implant overdenture and conventional overdentures and the biomechanics of each system. In their in vivo study, the complete denture group developed a more even pressure distribution at an average of 17.7 $\pm$ 4.81 kPa with lower ridge resorption. The implant overdenture group generated an uneven distribution of hydrostatic pressure and resulted in at least twice as much residual resorption than the complete denture groups. In their in vitro study, Sato et al. (2020) [21] focused on determining the appropriate attachment number and design in a mandibular overdenture and reported that ball attachments exerted the greatest effects on support and bracing—suitable for reducing oral mucosa pressure during mastication. A significant decrease in the oral mucosa pressure value and an increase in support and bracing when 2-implant dentures were applied—compared with complete dentures.

Table 4. In vitro and/or in silico studies investigating the pressures developed beneath dentures.

Study (Year)	Purpose	Methodology	Results
Assunção et al. (2009)	To evaluate the effect of different mucosa thicknesses and resiliency on the stress distribution of complete dentures and implant-retained overdentures using a two-dimensional finite element analysis.	Two-dimensional finite element analysis (FEA) in plane-strain condition	Implant-retained overdenture group showed higher stress values than complete denture group.
Chen et al. (2015)	To evaluate the differences in mucosal hydrostatic pressure of these three different (namely, complete, two and four implant-retained) denture treatments in a patient-specific setting.	Three-dimensional heterogeneous finite element (FE) model based on clinical CT scans	Bilateral pressure contour profile due to biting activity was observed. Distribution differed noticeably between the complete dentures and implant-retained dentures. More severe stress concentration observed at posterior ends of the mandible in 2-implant dentures, due to cantilever deflection during mastication.

Table 4. *Cont.*

Study (Year)	Purpose	Methodology	Results
Chen et al. (2016)	To develop an inverse procedure to determine these two biomechanical parameters by utilising in vivo experiment of contact pressure between partial denture and beneath mucosa through nonlinear finite element (FE) analysis and surrogate response surface (RS) modelling technique.	Three-dimensional patient specific FE model	FEA provides feasible approach to modelling load transfer, so it is difficult to assign realistic mucosa properties. Mucosal condition can vary significantly between individuals, and change across different types of mucosa (e.g., masticatory, lining) within the same subject.
Sato et al. (2020)	To determine the appropriate attachment and design of a denture base for mandibular implant overdenture (IOD), the oral mucosa pressure caused by mandibular implant overdentures was measured using edentulous jaw models with various attachments.	Precision universal testing machine, Instron 8874, (experimental mandibular edentulous jaw model with 1.5 mm thick artificial oral mucosa)	Ball attachments exerted greatest effects on support and bracing—suitable for reducing oral mucosa pressure during mastication. Significant decrease in oral mucosa pressure value and increase in support and bracing when 2-implant dentures were applied—compared with complete dentures.
Źmudzki et al. (2012)	To verify the hypothesis that the lower denture causes remarkable mucous membrane overloading resulting from destabilisation of the denture under oblique mastication forces.	Finite element method non-linear analysis	The pressure on the surface of a mucous membrane beneath a denture that was loaded in a stable manner with a vertical occlusal force of 100 N was lower than the pain threshold. The lateral mastication forces destabilised the denture by means of tilting it and reducing its supporting area. Significant pressures calculated for the destabilisation are consistent with the clinically observed decrease or a complete lack of chewing efficiency in the cases of unfavourable foundation conditions.
Źmudzki et al. (2018)	To determine whether the pressures developed beneath a removable mandibular complete denture during mastication would exceed the average pressure–pain threshold in patients for whom the denture foundation had an acceptable load-bearing capacity.	Finite element analysis–modelling ANSYS software	The denture was held to the mucosa under vertical force and a maximum pressure of 203 kPa. This means that the denture was supported not only by the denture foundation but also by the nonworking-side occlusal contact and had a downwardly directed stabilising reaction force. In delayed nonworking-side occlusal contact, the pressure beneath the denture was 783 kPa (>pressure–pain threshold) compared with 484 kPa (<pressure–pain threshold) in prompt nonworking-side occlusal contact. Despite the lower reaction force of the foundation in delayed nonworking-side occlusal contact, the pressure beneath the denture increased, indicating a reduction in the load transfer area due to the inclined position of the denture.

4. Discussion

Numerous in vivo, in vitro and in silico studies have attempted to evaluate the pressures under complete denture bases; however, because of the complexity and difficulty of replicating intraoral cavity conditions, results from this topic of interest can be variable, inaccurate and unreliable. Moreover, there is another layer of complexity as past studies investigate different designs and combinations of dentures, such as complete dentures, implant overdentures with a different number of implant supports.

An initial observation of the in vivo studies [6–14,18–20] demonstrates that there is no consistency in regards to the number of participants nor the types of participants involved, as differences in age and gender were also observed (Table 5). Several studies only looked at a single patient for their study [12,13,18,19], in which they evaluated pressure measuring systems and validated their study using data obtained from a singular individual. In contrast, Józefowicz [11] observed 50 patients in the first part of the study focusing on numerous landmarks of the edentulous maxillae, and then 475 patients in the second part of the investigation, which only looked at one region. Józefowicz [11] investigated the gum softness by measuring pressure yielding of the maxillary mucoperiosteum. Although he did not directly measure the pressure or pain threshold, the findings indicate the ability of oral mucosa to conform to change under pressure and demonstrates how this can ultimately affect the construction of the denture.

Table 5. In vivo studies investigating the pressures developed beneath dentures.

Study (Year)	Purpose	No. of Participants	Results
Ahmad et al. (2015)	To investigate and compare the residual ridge resorption (RRR) induced by an implant-retained overdenture (IRO) and associative biomechanics and by a conventional complete denture (CD) without implants.	n = 29 IRO (n = 8 m, 12 f) CD (n = 3 m, 6 f)	CD developed more even pressure distribution at average of 17.7 ± 4.81 kPa with lower RRR. IRO generated uneven distribution of hydrostatic pressure and resulted in at least twice as much RRR as CD.
Avci & Aslan (1991)	To present a “closed” hydraulic pressure measuring system capable of measuring pressures at the denture base–mucosal surface interface (to measure the swallowing pressures of edentulous patients for various occlusal vertical dimensions).	n = 1	A new “closed” hydraulic pressure measuring system is presented and is capable of measuring pressures at the denture base–mucosal surface interface and has three main parts. These are: (1) receptors that receive the pressures, (2) pressure transducers that convert the hydraulic pressures to electrical signals, and (3) a polygraph that amplifies and records the electrical signals coming from the pressure transducers. By means of a flexible membrane on the receptor, complete contact between the mucosa and the membrane can be obtained, which is the principal advantage of this system.
Berg et al. (1967)	To observe and define the relationships between pressures involved in denture-bearing tissue compressibility, vascular bed embarrassment, comfort threshold, adaptation of denture impression materials, and the physiological qualities of the completed prosthetic appliance, which include functional contact with edentulous ridges.	n = 6 (edentulous)	There is a relationship between the pressures involved in denture supporting vascular bed embarrassment and comfort threshold.
Cutright et al. (1976)	To observe pressure movements (waves) beneath the dentures during various masticatory and non-masticatory activities and the forces exerted against the different tissue sites beneath a denture during masticatory and non-masticatory movement.	n = 4	Non-masticatory movements exerted equal or much greater pressure than masticatory movements. Older patients produced generally lower ranges of pressure than young patients. Duration of denture wearing correlated with age—longer the denture worn, lower pressure ranges.

Table 5. *Cont.*

Study (Year)	Purpose	No. of Participants	Results
Józefowicz (1972)	To obtain reliable data as to the yielding of the maxillary mucoperiosteum by means of a method which would give comparative results and to explore the influence of denture wearing on the yielding of maxillary mucoperiosteum.	Part 1: $n = 50$ (40–79 years with edentulous maxillae) Part 2: $n = 475$ (40–79 years with edentulous maxillae)	Denture wearers have significantly higher periosteum yielding of residual ridges and torus platinus than non-denture wearers. Higher mucoperiosteum yielding in denture wearers connected to greater thickness of mucoperiosteum. Mucoperiosteum of fatty and glandular palatal zones have higher pressure yielding than that of other areas of edentulous maxillae.
Kubo et al. (2009)	To develop a system to measure the pressure distribution under the base of a removable partial denture (RPD) and to apply it in vivo.	$n = 1$	During maximal voluntary clenching, pressure distribution changed with the clenching level, and the highest pressure was registered near the residual ridge crest and lowest pressures always measured on lingual side. The pressure distribution also changed according to the number of occlusal rests.
Ogawa et al. (2004)	To examine regional differences and correlations of PPT in edentulous oral mucosa.	$n = 15$ (8 edentulous m, 7 edentulous f)	Different areas of edentulous oral mucosa have different PPT and that PPT varies proportionally in selected areas. PPT increased from the anterior to posterior alveolus in both maxilla and mandible, but decreased from the anterior palate to the posterior palate. PPT decreased from the ridge crest to the buccal vestibule.
Roedema (1976)	To determine the effect of reducing the occlusal table of a complete denture on masticatory pressures developed between supporting mucosal tissues and the base of the prosthesis.	$n = 1$	Direct inverse relationship between mean pressures at crest of residual ridge and width of occlusal table, consistent with findings of other investigators.
Shi et al. (1998)	To investigate the maximum ability of the masticatory mucosa under the denture base to bear bite force by measuring the stress-bearing area in patients, testing the maximum bite force in the same complete denture-wearers, and analysing the relationship between the force and the stress-bearing area.	$n = 31$ (18 edentulous m, 13 edentulous f)	Significant positive correlation between the MBF (the mean was 15.13 kg in men and 11.39 kg in women) and the PAM (the mean was 17.15 cm^2 in men and 14.46 cm^2 in women). No significant difference between the mean of the SBA in men (0.89 kg/cm^2) and the mean of the SBA in women (0.79 kg/cm^2). Mean value of the maximum pressure borne by the mandibular edentulous region was 82 kPa (0.84 kg/cm^2).
Tanaka et al. (2004)	To investigate the effects of denture wearing and bite force on the pressure–pain threshold (PPT) of edentulous oral mucosa.	$n = 35$ (10 elderly dentate m, 8 elderly edentulous m, 10 elderly dentate f, 7 elderly edentulous f)	The mid palate showed 200–300% higher PPT than the buccal alveolar mucosa (two-way ANOVA, $p < 0.0001$). Denture-wearing patients exhibited 40% lower palatal PPT than non-denture-wearing patients. In denture-wearing patients, PPT in the selected areas of the oral mucosa was negatively correlated with bite force. Denture wearing may reduce PPT in selected areas of the edentulous oral mucosa, and the PPT reduction may be associated with mechanical stress on the mucosa generated by bite force.

Table 5. *Cont.*

Study (Year)	Purpose	No. of Participants	Results
Watson & Abdul (1984)	To discuss the development of a simple, inexpensive strain gauge based pressure transducer, for use at the denture base–mucosa surface interface.	*n* = 1	Subjects tended to limit their chewing pressures to a narrow range independent of the type of food eaten. Estimated that the area of the lower denture was about half that of the maxillary denture and suggested that pressures could become exceedingly high on the lower denture-bearing mucosa during chewing, particularly of fibrous or nutty food.
Watson & Huggett (1987)	To evaluate pressures produced under complete upper and lower dentures at the denture base–mucosal surface interface.	*n* = 4 patients (1 m, 3 f)	The younger patients and patients with the shortest chewing sequences had more reproducible pressure peak values. The two food types have quite different effects both on the pressure values recorded and the duration of the chewing sequence. The pressure applied to the lower transducers while chewing peanuts was almost 50% greater than that when carrot was masticated. The total peak pressure was also markedly increased in the case of peanuts.

The extent of edentulism differed across in vivo studies and this meant that there were some variations in the design of prostheses as some studies included conventional complete dentures or implant overdentures [5,15,20,21], whereas partially edentulous patients were rehabilitated with removable partial dentures [12,16,17]. While it is acknowledged that the amount and pattern of pressure exerted by removable prostheses would differ between tooth-mucosa supported and mucosa-support only situations, there is yet to be any clinical report investigating the correlation between the extent of edentulism and pressure distribution on the edentulous ridges.

Various pressure sensor systems, such as pressure transducers [8], tactile sensor sheets [12,16], pressure algometers including pressure sensitive strain gauges [7], pressure gauges [10] and hydraulic pressure transducers [18], were used to measure pressure or the pressure–pain threshold. While it is useful to see the various results associated with different pressure sensor systems, these devices are designed to focus on a single intraoral position (i.e., the hard palate) and may not be able to provide continuous pressure readings during normal intraoral function. It would be more beneficial to use appropriate pressure measuring systems in various locations so that the amount of pressure and its distributions can be observed. This would then give further insights into the correlation between the pressure measurements and pain threshold.

There were various methods to induce intraoral pressure such as counting one to ten, chewing assorted textured foods or swallowing [8]. While these methods utilise everyday functional intraoral movement, they also have limitations in that the frequency, intensity and pattern of force produced by individuals vary. Therefore, the methodology should be standardised between participants. Another method using an algometer to apply pressure to the patient's oral mucosa to measure the PPT has the advantage that the rate at which manual force is applied is consistent to provide reliability in the results [6,7].

A recent study by Sato et al. (2020), which measured the oral mucosa pressure caused by mandibular implant overdentures and various attachment systems [21], provides adequate reference for future studies investigating oral mucosa pressure. However, there were some limitations within this study. A precision universal testing machine, Instron 8874, was used to measure the in vitro pressures yet there was no regard to specifying the size of the load cell used in conjunction with the configuration testing. Moreover, the study used only acrylic complete dentures as their prosthesis of choice and did not use a comparison group, such as using any mucosal tissue to simulate accurate clinical environment, which further resulted in a lack of validity in their findings.

In more recent years, FEA simulations have been used in in silico studies when investigating the biomechanical responses of edentulous mucosa [16] by estimating the load of the masticatory force experienced beneath the prosthesis [17]. However, due to the nature of FEA studies and the finite element modelling (FEM) software, clinical data are required to mimic the function and anatomy of the edentulous jaws. For this reason, any assumptions made within the respective FEA studies are critical as they influence the accuracy and validity of the experiment [15,17]. Źmudzki et al. [17] further highlighted the inconsistencies associated with FEA research and suggested errors when the pressures measured beneath dentures were lower than the average PPT. An alternative method in validating results from FEA investigations was demonstrated by Chen et al. [16], where clinical data were used to characterise the mucosal tissue and the results from their simulated study were subsequently corroborated with clinical data. This assisted in determining the biomechanical parameters, Poisson's ratio of oral mucosa and the friction coefficient between the denture base and mucosa, using an inverse method. The mechanical properties of other materials were based on data from previous FE studies. Although in vitro studies and FEA offer a feasible approach to simulating in vivo situations, there are certain limitations, such as applying assumptions on the responses of the biological system or the difficulty of setting up a clinically accurate environment. Therefore, any conclusions made based on these measurements cannot be extrapolated to the entirety of the edentulous population and, hence, it is essential that in vivo measurements are used as the baseline data for in vitro studies as part of the validation process.

Two studies reported that the PPT of an edentulous patient was approximately 630 kPa [4,17] and that there was a strong relationship between PPT and different areas of the edentulous oral mucosa [7], such as the mandibular crest recording the greatest PPT measurement [14] due to the location of the occlusal load during masticatory function. Nevertheless, the PPT variable between individuals [4] and the changes in intraoral pressure were based on the different patient activities, such as mastication, speech and swallowing [8]. There also seemed to be a generalised pressure pattern occurring between the duration of denture-wearing and age, in which lower pressure ranges were observed for long-term denture wearers [8]. Older patients seemed to produce lower pressure ranges as they were more skillful in controlling their dentures during normal function. For this reason, the correlation between denture–mucosa pressure and PPT, and how these results affect the outcome of the patient's quality of life, has yet to be fully investigated (although few studies have referred to it).

The pressure ranges measured were variable among included studies. Numerous studies presented their pressure range and distribution results using graphical and/or diagrammatical measurements [5–7,13,15–17,20,21], which is difficult to interpret accurately as well as objectively. Additionally, across all studies, the pressure units were not standardised which led to the inability to compare the measurements recorded in units other than mPa or kPa [8,10].

There is still a lack of methodology where the ranges and distribution of pressure developed under the denture base and applied to the edentulous mucosa can be measured. A future study should therefore focus on developing a standardised way of measuring the mucosal pressure related to edentulous patients.

5. Conclusions

According to a systematic review conducted, past studies that attempted to measure the denture–mucosa pressure distribution varied greatly in their methodology which limited a valid comparison. Despite the clinical significance, there is yet to be any baseline value which can be universally applied for future studies to correlate the oral mucosa pressure PPT of edentulous patients. The authors encourage further clinical and in vitro/in silico research evaluating the pressure distribution in oral mucosa, especially comparing different designs of prosthesis under a controlled setting.

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References

1. Emami, E.; De Souza, R.F.; Kabawat, M.; Feine, J.S. The Impact of Edentulism on Oral and General Health. *Int. J. Dent.* **2013**, *2013*, 498305. [CrossRef] [PubMed]
2. Petersen, P.E.; Kandelman, D.; Arpin, S.; Ogawa, H. Global oral health of older people—Call for public health action. *Community Dent. Health* **2010**, *27* (Suppl. 2), 257–268. [PubMed]
3. World Health Organisation (WHO). Available online: https://www.who.int/news-room/fact-sheets/detail/oral-health (accessed on 25 March 2020).
4. Źmudzki, J.; Chladek, G.; Kasperski, J. The influence of a complete lower denture destabilization on the pressure of the mucous membrane foundation. *Acta. Bioeng. Biomech.* **2012**, *14*, 67–73. [PubMed]
5. Chen, J.; Ahmad, R.; Suenaga, H.; Li, W.; Swain, M.; Li, Q. A comparative study on complete and implant retained denture treatments: A biomechanics perspective. *J. Biomech.* **2015**, *48*, 512–519. [CrossRef] [PubMed]
6. Tanaka, M.; Ogimoto, T.; Koyano, K.; Ogawa, T. Denture wearing and strong bite force reduce pressure pain threshold of edentulous oral mucosa. *J. Oral Rehabil.* **2004**, *31*, 873–878. [CrossRef]
7. Ogawa, T.; Tanaka, M.; Ogimoto, T.; Okushi, N.; Koyano, K.; Takeuchi, K. Mapping, profiling and clustering of pressure pain threshold (PPT) in edentulous oral mucosa. *J. Dent.* **2004**, *32*, 219–228. [CrossRef]
8. Cutright, D.E.; Brudvik, J.S.; Gay, W.D.; Selting, W.J. Tissue pressure under complete maxillary dentures. *J. Prosthet. Dent.* **1976**, *35*, 160–170. [CrossRef]
9. Shi, S.G.; Wu, S.; Lu, L.; Imai, A.; Tanaka, M.; Kawazoe, T. The stress-bearing ability of mucosa in complete denture-wearers. *Chin. J. Dent. Res. Off. J. Sci. Sect. Chin. Stomatol. Assoc. CSA* **1998**, *1*, 41–45.
10. Berg, T., Jr.; Chase, W.W.; Ray, K. Denture base pressure tests. *J. Prosthet. Dent.* **1967**, *17*, 540–548. [CrossRef]
11. Józefowicz, W. Pressure yielding of the maxillary mucoperiosteum. *J. Prosthet. Dent.* **1972**, *27*, 600–606. [CrossRef]
12. Kubo, K.; Kawata, T.; Suenaga, H.; Yoda, N.; Shigemitsu, R.; Ogawa, T.; Sasaki, K. Development of in vivo measuring system of the pressure distribution under the denture base of removable partial denture. *J. Prosthodont. Res.* **2009**, *53*, 15–21. [CrossRef]
13. Roedema, W.H. Relationship between the width of the occlusal table and pressures under dentures during function. *J. Prosthet. Dent.* **1976**, *36*, 24–34. [CrossRef]
14. Watson, C.J.; Huggett, R. Pressures recorded at the denture base-mucosal surface interface in complete denture wearers. *J. Oral Rehabil.* **1987**, *14*, 575–589. [CrossRef] [PubMed]
15. Assunção, W.G.; Barão, V.A.R.; Tabata, L.F.; De Sousa, E.A.C.; Gomes, A.; Delben, J.A. Comparison between complete denture and implant-retained overdenture: Effect of different mucosa thickness and resiliency on stress distribution. *Gerodontology* **2009**, *26*, 273–281. [CrossRef] [PubMed]
16. Chen, J.; Suenaga, H.; Hogg, M.; Li, W.; Swain, M.; Li, Q. Determination of oral mucosal Poisson's ratio and coefficient of friction from in-vivo contact pressure measurements. *Comput. Methods Biomech. Biomed. Eng.* **2016**, *19*, 357–365. [CrossRef] [PubMed]
17. Źmudzki, J.; Chladek, G.; Malara, P. Use of finite element analysis for the assessment of biomechanical factors related to pain sensation beneath complete dentures during mastication. *J. Prosthet. Dent.* **2018**, *120*, 934–941. [CrossRef] [PubMed]
18. Avci, M.; Aslan, Y. Measuring pressures under maxillary complete dentures during swallowing at various occlusal vertical dimensions. Part I: A new hydraulic pressure measuring system. *J. Prosthet. Dent.* **1991**, *65*, 661–664.
19. Watson, C.J.; Abdul Wahab, M.D. The development of an inexpensive pressure transducer for use at the denture base-mucosal surface interface. *Br. Dent. J.* **1984**, *156*, 135–140. [CrossRef] [PubMed]
20. Ahmad, R.; Chen, J.; Abu Hassan, M.I.; Li, Q.; Swain, M. Investigation of mucosa-induced residual ridge resorption under implant-retained overdentures and complete dentures in the mandible. *Int. J. Oral Maxillofac. Implant.* **2015**, *30*, 657–666. [CrossRef] [PubMed]
21. Sato, H.; Kobayashi, T.; Nomura, T.; Tanabe, N.; Takafuji, K.; Kihara, H.; Kondo, H. Oral mucosa pressure caused by mandibular implant overdenture with different types of attachments. *J. Prosthodont. Res.* **2020**, *64*, 145–151. [CrossRef] [PubMed]