Can bite-force measurement play a role in dental treatment planning, clinical trials, and survival outcomes? A literature review and clinical recommendations

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Bite force (occlusal force) may play a significant role in patient treatment outcomes. However, as a diagnostic risk assessment tool, it has been examined in the literature but is not commonly utilized by practicing clinicians and in academic studies. This diagnostic evaluation may assist the dental clinician in planning tooth- and implant-supported restorations, as damage to the tooth, implant, or restoration may be dependent upon a restoration's resistance to loading conditions. The overall bite force has been estimated to be up to 2,000 N, with a clear sexual dimorphism and age dependence. The magnitude of these forces along the dental arch have been shown to be elevated in the posterior compared to the anterior region. The bite force magnitude has been inversely related to the proprioception, as a significant increase in bite force is seen in patients with endodontically treated teeth as compared to their vital teeth. Bite force has been linked to chewing efficiency, quality of life, and implicated in the life expectancy of the restorations. Restoration life expectancies have been associated with the material selection and preparation design parameters, both of which may be affected by masticatory bite force. Treatment planning criteria for preparation strategies affected by bite force include tooth location, material selection, occlusion pathways, and subsequent occlusal reduction amounts. When implants are used in patients with elevated magnitude of bite force, an increase in the number and diameter of the implants as well as occlusions with reduced occlusal tables buccolingually and lighter contacts may be recommended. An understanding of the magnitude and load of a patient's bite force can assist the dental clinician in the design of dental treatments along with other standard risk assessment criteria.
(Quintessence Int 2022;53:2–12; doi: 10.3290/j.qi.b3044939)

Key words: dental prostheses, failure, occlusal force, occlusal load, restoration

Occlusion, by definition, relates to the contacts between dental antagonists. Bite force (occlusal force), from the muscles through the occlusal contact area, results in load that may produce damage to the masticatory system depending on the magnitude, frequency, direction of forces, and number of teeth present.[1] Therefore, bite force may be considered a key indicator of a healthy masticatory system, in that a deficiency or surplus can be implicated in multiple disorders and dental complication. Amongst others, these disorders include temporomandibular disorders (TMD),[2] bruxism,[3] restoration failure,[4] bone resorption,[5] and neurologic diseases.[6] Knowledge of bite force may be critical in understanding the oral health of patients. An excessive bite force may affect long-term survivability of a restoration as well the long-term health of the masticatory apparatus.[7]

This review aims to highlight the important, yet often overlooked, aspect of the masticatory system – the bite force. When combined with knowledge of the oral habits and conditions, this information can help dental professionals plan the appropriate restorations for their patients in the treatment of the compromised dentition.

Method and materials

The following databases were extensively searched for literature on the relevant topics (accessed from January to September 2021): PubMed (US National Library of Medicine); Google Scholar (Google); and the Cochrane Library. The search strategy consisted of focusing on the following terms in the search

doi: 10.3290/j.qi.b3044939

engines to identify relevant literature. More specifically, the following terms have been used in the aforementioned databases: (bite force) AND (dent*); (bite force) AND (dentist *) AND (failure); (bite force) AND (dentist*) AND (dental restoration failure) AND (crown OR dental implant).

Selection criteria included any article written in English and discussing the topic of bite force in dentistry up to March 2022. This paper has been developed based on recent systematic reviews, case studies, clinical studies, and retrospective studies, as well as foundation studies that have established the science of bite force in dentistry. The authors meticulously assessed a total of 543 articles that fulfilled the selection criteria, which were further reviewed for their relevance on the use of bite force in the study of restorative dentistry. More specifically, to critically review how bite force is measured, whether bite force influence dental restoration failure, the effect of bite force on dental restorations, and the theoretical bite force limit that common dental restorative materials can withstand.

The biomechanics of bite force

In order to understand bite force, it is important to examine the biomechanics of the human jaw. The forces from masticatory muscles transfer their load through the dentition during occlusion, and while some horizontal (or non-axial) load is applied normal to the contact surfaces, the principal action of the force is vertical (or axial) to the long axis of the teeth.[8,9] The load distribution of the bite force is predominantly on the posterior teeth, with up to three times greater forces than the anterior, due in part from the masticatory muscle function in the different regions,[10] and the morphology of the jaw being a complex lever system.[9,11] Additionally, the morphology of the mandible is quite well adapted to the cyclical nature of these large clenching force distributions, with a stiffer mandible that includes a large mandibular corpus to withstand the repeated stresses of chewing.[12]

Occlusal contact is a biomechanical factor that can significantly vary a patient's bite force. Studies have shown that there is up to 20% decrease in bite force due to missing teeth or malocclusion.[11,13] Patients with malocclusions, as defined by dental and Angle classification, in particular Class III (both dental and skeletal) patients with decreased vertical overlap, display higher bite forces in posterior teeth compared to Class I and II patients.[14] Another study demonstrated that malocclusion has an unfavorable effect on bite force, where the authors found an similar increase in forces with Class III patients as compared to other patient groups.[15]

As proposed by Frost,[16] there is a range of strain within the bone tissue that is required to maintain homeostasis, as an elevated strain can cause fracture and decreased strain (or disuse) can cause tissue resorption.[17] This microstrain can only be achieved from the transfer of forces to the bone itself.[17,18] Though no clinically established thresholds exist, an association between loading and bone response has been established.[19-21] In the stress-bearing region of nonmalocclusion dentate patients, the force is transmitted through natural dentition via the cortical and trabecular bone.[22] Edentulous or partially edentulous patients are deficient in this transfer of forces due to no direct occlusal contact, dissipation by the gingiva, or through sparsely placed implants.[5] This is readily apparent in edentulous mandibular ridge resorption, where the unstimulated mandible decreases significantly.[23] Additionally, the measured force and muscle thickness of edentulous patients has been shown to be significantly lower than those of dentate patients.[24,25] It can be inferred that as a result of this decreased force, there would be a decrease in strain in the bone, which may cause the significant bone loss seen in edentulous patients.[5,23,26,27] Loss of bone, from little to no strain, can be as much as 4 mm after the first year of tooth removal, and at a constant rate of resorption per year.[27-29] The majority of this loss is in the mandible's anterior section, which is four times greater than that of the maxilla.[27] Thus, some nominal level of bite force can be deemed necessary for maintaining healthy bone tissue through imposed strain, but how does the force vary in the population?

Multiple researchers have shown that bite force levels are correlated by age and sex.[14,30-33] Tables 1 and 2 showcase the measured bite forces and the conclusions, respectively, arrived upon by the studies' authors as it pertains to bite force. Bite force for all groups studied varied greatly between 50 to 2,000 N, and while each study measured bite force in a different way, women were consistently found to have half to two-thirds the levels found in men.[10,30,31] The authors noted another important sexual dimorphism, that men have sharper, shorter bites (high impulse power) than the slow and reduced bite force in women (low impulse power), which is an important factor when considering the relatively low toughness (measure of energy absorption) of common dental materials.[48] The age of dentate patients was also closely tied to the maximal bite force, with a lower force recorded in children, and a maximal force in early adulthood trending slightly lower with increasing age.[30,39,47,49] This marked difference has been proposed to be due to reduced musculature in women, decrease muscle density with age, and sexual dimorphism in the occlusal contact area.[13,50]

doi: 10.3290/j.qi.b3044939

Table 1 Average maximum bite force estimations based on region of natural adult full dentition (excluding third molar) in the literature

			Bite force (N)*							
			Tooth							
Study	Method (surface/ tool)	Sample size (male/ female)	Second molar	First molar	Second premolar	First premolar	Canine	Lateral incisor	Central incisor	Full arch (n)
Hidaka et al[34†]	FA / DPS	9 m / 3 f	325	167	50	29	17	5	10	1,181
Kumagai et al[35]	FA / DPS	13 m / 3 f	365/353 (R/L)		65/57 (R/L)			65 (Bi)		905
Shinogaya et al[36]	FA / DPS	22 m / 24 f	NA	NA	NA	NA	NA	NA	NA	1,634 m / 1,071 f
Hattori et al[9]	FA / DPS	22 m / 8 f	NA	NA	NA	NA	NA	NA	NA	777
Braun et al[32]	Bi / PGT	86 m / 56 f	NA	814 m / 615 f	NA	NA	NA	NA	NA	NA
Varga et al[37]	ST / OFM	14 m / 16 f	NA	778 m / 482 f	NA	NA	NA	NA	NA	NA
Serra et al[38]	ST / OFM	14 m / 20 f	NA	812 m / 618 f	NA	615 m / 435 f		NA	231 (Bi)	NA
Bakke et al[39]	ST / SGT	10 m / 10 f	NA	531 m / 433 f	NA	NA	NA	NA	NA	NA
Kleinfelder and Ludwig[40]	ST / SGT	6 m / 4 f		534		378	NA	NA	NA	NA
Ferrario et al[41]	ST / SGT	36 m / 16 f	294 m / 222 f	306 m / 234 f	291 m / 206 f	254 m / 179 f	190 m / 120 f	139 m / 96 f	146 m / 94 f	NA
Van Der Bilt et al[42]	ST / SGT	13 m / 68 f	NA	490/652 m (ST/Bi); 418/553 f (ST/Bi)	NA	NA	NA	NA	NA	NA
Lepley et al[43]	ST / SGT	15 m / 15 f	NA	384	NA	374	NA	NA	NA	NA
Amid et al[44]	ST / FfS	50 m / 50 f	NA	571/555/560 (Bi/L/R)	NA	NA	NA	NA	269 (Bi)	NA
Khan et al[45†]	ST / FfS	52 m / 43 f	NA	756 m/621 f (D); 548 m / 458 f (Nd)	NA	NA	NA	NA	NA	NA
Takaki et al[46]	ST / DDK	10 m / 10 f	NA	284 m / 305 f	NA	NA	NA	NA	NA	NA
Poli et al[47]	ST / DDK	39 m / 40 f	NA	618/598 m (R/L); 500/ 491 f (R/L)	NA	NA	NA	NA	NA	NA

*The bite force measurement methodology was performed bilaterally (Bi) on the left and right tooth antagonists, unilaterally on a single tooth (ST) on either the left (L) or right (R) side (if available), or along the full dental arch (FA). The technologies used were a custom strain gauge transducer (SGT), a custom pressure gauge transducer (PGT), the Dental Prescale System (DPS, Fuji Film), an Occlusal Force Meter (OFM, Nagano Keiki), Digital Dynamometer (DDK, Kratos), or a Flexiforce Sensor (FfS, Tekscan). Any merged cells indicate bite force was pooled for those specific teeth.
†Hidaka et al[34] and Khan et al[45] performed their studies on the self-declared preferred/dominant and non-preferred/dominant sides.

Despite variations with sex and age, it has been shown that the molar regions exhibit the highest forces.[31,33] These regions experience the highest force values, with as much as 80% of the full arch bite force in the bilateral molar region of the oral cavity,[9,10,36,51] and up to 58% of the full arch bite force on the preferred chewing side.[9,45] Even in the loss of dentition, the posterior region could exert higher forces upon permanent restoration due to increased muscle function of these patients, approaching the muscle function of dentate patients.[25,52]

Though there are varied levels of bite force in the general population, a clear understanding of this important biomechanical component of the oral cavity should be considered during the placement of the dental restoration. This maximum bite force can dictate the strain to maintain supportive bone tissue and the stress capacity a dental restoration should be able to withstand during regular use, to ultimately reduce the risk of failures.[53,54] In order to understand how the bite force affects the stress and strain within the oral cavity, it must be quantitatively measured.

doi: 10.3290/j.qi.b3044939

How is bite force assessed in the literature?

Maximum voluntary bite force has been established in the literature as a method for evaluation of occlusion and masticatory function.[36,51,55] Several factors that influence bite force include the condition of the dentition, the length and strength of the jaw-closing muscles, jaw separation, presence of nonvital teeth, and the pain threshold of the subject.[2,56,57] The total axial bite force varies within the regions of the oral cavity and is greatest in the molar region, as seen in Table 1. Lepley et al[43] demonstrated that maximum premolar and molar tooth contact area and bite forces contributed to significant correlations with total chewing cycle duration and masticatory performance. The literature demonstrates many methods for evaluating bite forces during chewing and clenching. These methods involve measuring vertical force using devices that are mechanical, electrical, or a combination of both. The first bite force device, called a gnathodynamometer, was built by Borelli in 1681.[2,58,59] Bite force devices use load cell technology to convert force to electrical signal that may be based on strain-gauge, pressure, or piezoelectric transducers.[58] Currently there exists a limited number of marketable bite force measurement devices (Figs 1 and 2). The T-Scan system (Tekscan) is a device used to measure occlusal contact strength. The sensor is embedded with pressure-sensing resistive ink, in order to measure occlusal contact area and strength proportion.[60] It is considered a complement to articulating paper to detect the number and location of occlusal contacts as well as to compare proportional forces made at specific time points.[61] However, the ability of the T-Scan to quantify overall bite force has not been demonstrated in the current models.[62] Complementary to the T-Scan, a full arch bite force measurement device, the Innobyte (Kube Innovation), which functions by converting the pressure of a compressed volume during voluntary biting events to Newtons, is capable of quantifying total vertical bite force.[63]

Table 1 shows the bite force along the dental arch from the reviewed studies and how they were measured. While certain studies examined the mean bite force along the full dental arch, the majority were performed on single tooth antagonists, and most on the mandibular first molar using prototype sensors. The studies that were performed on single teeth antagonists exhibited higher mean bite forces than their full-arch individual counterparts. This variation can be due to intermolar separation,[64] muscle recruitment,[56,65] biting surface of sensor,[38] or dominant chewing side,[45] amongst other causes. Regardless of the published mean bite force, each study demonstrated a high variability between study participants. This variability underscores the need to assess the bite force in patients to understand how these range of forces influences the survivability of restorative treatments in the general population.

In Table 2 the studies showcased in Table 1 had their conclusions summarized, as they pertain to bite force in the sample population, and the study limitations were analyzed. The majority (89%) of the focused studies had a limited sample population, which could introduce biases that affect the bite force variability. Sample size to obtain representative results of a population is a complex task; however, the majority of these studies had fewer than 30 participants in each analyzed group, which is too few to represent certain populations with sufficient confidence level (outside of a pilot study).[66] Also, the majority (69%) of the studies did not analyze the measurement device for accuracy and/or repeatability, or the device had a measurement error of greater than 10%, which could arbitrarily increase or decrease the published bite force values and its variability. A select few studies pooled their bite force data from females and males, as well as left and right, when performing statistical analysis. The consistently lower bite in females and nonpreferred biting side can introduce biases to a study's parametric analyses, which can lead to statistical errors. Overall, the studies can be considered pilot studies into bite force measurement; however, studies with larger cohorts using measurement devices with proven precision and accuracy are required to examine the conclusions of these authors.

Bite force effects on implant fixtures and implant restorations

A systematic review on improving masticatory performance, bite force, nutritional state, and patient's satisfaction with mandibular implant overdentures concluded that treating complete denture wearers with implants to support their denture improves their chewing efficiency, increases maximum bite force, and improves satisfaction.[67,68] Two recent comparative studies by Possebon et al[69] and Vo et al[70] came to the same conclusions. Functional stress on dental implants may cause positive or negative consequences for bone tissue. A certain level of occlusal load is required for normal bone homeostasis, but when bite forces exceed the biologic load-bearing capacity of the supporting bone, it may result in loss of implant osseointegration or create implant mechanical complications.[19,70,71] A literature review of the etiology of dental implant fracture concluded that the use of a greater number of implants with wider diameters, mainly in the posterior regions, as well as optimized use and distributed occlusions should be considered to prevent implant loss from overloading.[20,72]

doi: 10.3290/j.qi.b3044939

Table 2 Assessment of the conclusions of the authors and the limitations of the referenced clinical studies on bite force

Study	Study conclusion	Study limitations*
Hidaka et al[34†]	Submaximal clenching is on preferred side. No preferential side at maximal clenching. Highest bite force in posterior, at mesial third of M1 and distal third of M2.	Limited sample size in comparison analysis. High reported error of measurement device.
Kumagai et al[35]	Number and area of tooth contacts increase as clenching increases. Molar bite force increases while other teeth decrease with an increase in clenching.	Limited sample size in comparison analysis. Pooled bite force data of each sex in overall analysis. No data on all masticatory muscles' contribution
Shinogaya et al[36]	Center of bite force at 75% anteroposterior and 50% left-right. Center of bite force not sex-, age-, ethnicity-dependent. Larger contact area and bite force in males vs females.	Limited sample in age/sex/ethnicity comparison analysis.
Hattori et al[9]	Large variability of number of contacts and maximal bite forces. Bite force slanted antero-posteriorly, cannot be explained by Class III lever system.	Limited sample in sex comparison analysis. Pooled bite force data of each sex in overall analysis. Repeatability of instrument not examined.
Braun et al[32]	Bite force correlated well with sex. Bite force not correlated with age, height, weight, orthodontic treatment, TMD symptoms, or missing teeth.	Limited sample in age comparison analysis. Pooled bite force data of each sex for each additional metric. Repeatability of instrument not examined.
Varga et al[37]	Bite force increases in 15- to 18-year-old male subjects, not in females. 18-year-old males had higher bite force in than all tested groups. BMI, morphology, and jaw function cannot be used to predict bite force.	Limited sample in age comparison analysis. Repeatability of instrument not examined.
Serra et al[38]	Bite force significantly higher on soft vs hard bite surfaces. Bite force was greatest in the molar region for both sexes.	Limited sample in age comparison analysis.
Bakke et al[39]	Bite force increased significantly up to 25 years old. Occlusal stability and number of teeth correlated significantly with bite force.	Limited sample in age comparison analysis. Fits were not significant for apparent bite force trends.
Kleinfelder and Ludwig[40]	Bite force not limited by decrease in periodontal ligament support. Posterior splinting of teeth increased bite force over molar teeth.	Limited sample in test and control for comparison analysis. Pooled bite force data of each sex in overall analysis.
Ferrario et al[41]	Lowest bite force on the incisors, largest force on the first molar. Larger bite force in males vs females.	Limited sample in sex comparison analysis. High reported error of measurement device.
Van Der Bilt et al[42]	Unilateral bite forces up to 30% lower than bilateral. Muscle activities lower in unilateral with bilateral clenching. Ipsilateral anterior temporal muscle higher activity than contralateral.	Limited sample in sex comparison analysis. Repeatability and accuracy of instrument not examined.
Lepley et al[43]	Larger contact areas had better masticatory performance. Masticatory performance is related tooth alignment, bite forces, and contact area.	Limited sample size in comparison analysis. Repeatability and accuracy of instrument not examined.
Amid et al[44]	Bilateral posterior bite forces were higher than posterior unilateral and anterior. Males had higher bite force than females.	Limited sample size in craniofacial comparison analysis. High reported error of measurement device.
Khan et al[45†]	Preferred side bite force higher than nonpreferred in males and females. Males higher bite force than females in preferred and nonpreferred side.	Repeatability and accuracy of instrument not examined.
Takaki et al[46]	Females bite force increase until adulthood then decreases in adulthood. Male bite force greater than in women independent of age groups.	Limited sample size in comparison analysis. Repeatability and accuracy of instrument not examined.
Poli et al[47]	Maximum bite force decreases with age. Males higher bite force than females, and no difference in right vs left sides.	Repeatability and accuracy of instrument not examined. Pooled bite force data of each sex in BMI analysis.

*Studies that based their bite force analysis on a population of less than 30 participants in each group were considered to have limited sample size. Studies that did not examine the measurement device for accuracy and/or repeatability, or had demonstrated a larger than high (>10%) measurement error were noted as such. Studies that performed their analysis of parameters on pooled data from females and males were noted as such.
†Hidaka et al[34] and Khan et al[45] performed their studies on the self-declared preferred/dominant and non-preferred/dominant sides.
BMI, body mass index.

Esquivel-Upshaw et al[73] concluded in their study analyzing fractures of randomized implant-supported fixed dental prostheses, that due to absence of a periodontal ligament, implant-supported prostheses should have minimal occlusion and lighter contacts than those supported by natural dentition. Prosthetic and implant fixture complications to excessive load-

doi: 10.3290/j.qi.b3044939

ing may be avoided by increasing the number of implants supporting a prosthesis and using implants with diameters greater than 3.3 mm. McDermott et al[74] commented, in their retrospective cohort study on dental implant complications, that an oral habit history including bruxism would have been beneficial to determine the effect on the outcomes. Kumararama and Chowdhary,[75] and previously Demenko et al,[76] concluded that the amount of stress in the bone around an implant, based on a numerical analysis of different masticatory loads through the various implant dimension, can be reduced by increasing the dimensions of the implant. Therefore, based on the masticatory bite force by a patient, a specific implant length and width can be correlated and recommended by the clinician.

Bite force and fatigue in restorative materials: in vitro and in silico

Amongst the etiologic causes of restoration failures, the highest remains mechanical fracture,[4,72,77-80] which has been shown to be region-specific and material-specific.[81] Under static loading conditions, a standard crown restoration has a fracture load of 900 to 4,000 N,[82,83] and implants fracture at a load of well over 1,000 N.[84] Bite force values of this magnitude are uncommon on a single tooth; however, under cyclical chewing forces the fatigue corrected loading conditions to failure of these materials could be as low as 400 N,[75,85] which is within the range of certain populations of patients.[7] This may be caused by the environment of the oral cavity, which is both moist and cyclically affected by temperature;[86-92] two parameters that have been shown to decrease the fatigue strength of dental materials by as much as tenfold.[86,88,89] When factoring in bacterial demineralization and surface wear, crack depth can be extended to critical levels, thus decreasing loads to fracture.[93] The presence of environmental stressors, crack depths, and cyclical forces increase the stress in these materials to critical levels that may exceed the material's modified fatigue strength. Despite the in vitro nature of these studies, the modified fatigue strength could highlight the potential limitation of certain dental materials in an environment that undergoes excessive cyclical thermomechanical stresses.

Due to clinical and ethical limitations, occlusal loads and dental restoration failures have not been correlated in any meaningful capacity.[4,71] However, current modeling algorithms have allowed researchers to predict loading conditions from a single tooth to the whole dental arch.[7,94-98] These in silico techniques predict, with clinically relevant loading conditions, stresses that range from 50 to 700 MPa, which can exceed fatigue strengths of commonly used dental materials.[99-102] In vivo validation of these predictive bite force models are actively being researched.[103] Although limited in their scope, these studies point towards a common theme: the presence of elevated contact stresses in the dental arch from clinically relevant bite forces. Clinicians can use these predictive models to help determine potential risks of restoration failure due, in part, from occlusal loads.

The failure mechanics of dental restorations can also be modeled based on crack propagation (continuum damage approach).[104,105] As fatigue failure has long been shown to be the result of subcritical crack growth,[48,88] current predictive models allow researchers not only to demonstrate what can fail, but also to estimate the time to failure based on crack dimensions and material properties. The models use relevant dimensioning of cracks from defects caused by manufacturing or regular teeth wear, and are able to determine lifetime of said teeth. Recently, research groups have validated the crack propagation model by fractographic analysis of recovered failed dental restorations,[95,106-108] and found fractures initiated, as predicted, from occlusal wear surfaces or other stress concentrators (threads, fossa, thin sections, etc).

When combining the in vitro experimental fatigue strength and stress modeling of restorative materials, a clear trend emerges: dental restorations can fail earlier than their prescribed service lifetime depending on applied stresses especially in the presence of crack-propagating defects. These stresses are be related to the occlusal loading from a measured bite force at the occlusal table. Thus, assessing a patient's bite force can help the clinician to understand the limitations of certain materials in relation to stresses and restorative preparations.

Bite force and the effect on the natural dentition and its restorative treatments

It has been well documented that endodontically treated teeth suffer greater amounts of fracture than their vital counterparts.[109,110] It has been theorized that some proprioception or mechanical sensation is lost after endodontic treatment.[111,112] This suggests that the pulp participates in controlling the load that is exerted on teeth during mastication, protecting the tooth from potentially harmful bite forces. A comparative cross-sectional study examined bite force in endodontically treated teeth to determine the importance of the dental pulp in controlling occlusal loads.[57] The maximum bite force was significantly higher in endodontically treated teeth compared with vital contralateral teeth. The authors concluded that human teeth possess intradental receptors that have non–pain-related

doi: 10.3290/j.qi.b3044939

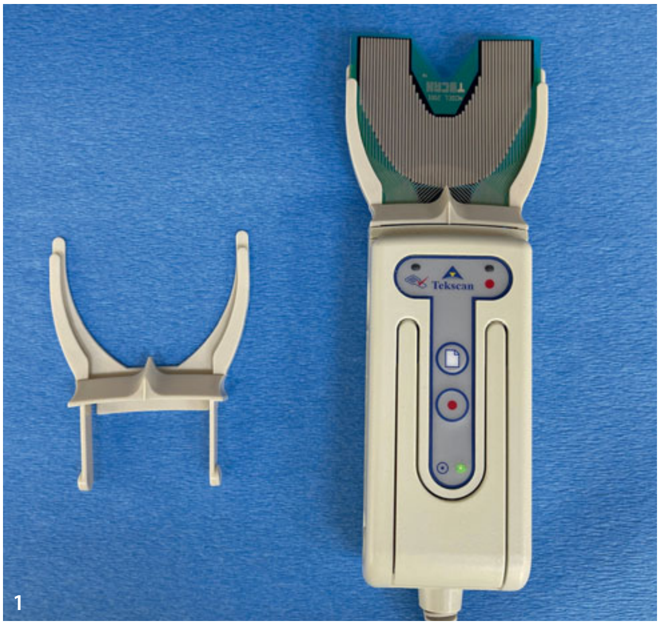

Fig 1 T-Scan occlusal analysis system (Tekscan).

Fig 2 Innobyte bite force measurement device (Kube Innovation).

functions such as detecting harmful pressure and protecting the teeth during mastication. Due to the natural asymmetry, contralateral forces may vary slightly, which may have increased the assessed bite force in these studies, as previously shown.[45]

Several studies have demonstrated that individuals with loss of attachment, in the absence of inflammation, may have reduced proprioception of biting force due to the fact that loading forces during mastication are controlled by the proprioceptors of the periodontal ligament.[10,111,113-116] These proprioceptors have been shown, in some studies, to be in a negative feedback mechanism with the jaw elevator muscles, in that the absence of the receptors there may be an increase of the maximum voluntary bite force.[13,111,115] Other studies did not show any significant difference in the bite force,[40,117] and the discrepancy between these studies could be attributed to the differences of recording devices and measurement areas. Another study measuring the bite force with cross-arch bilateral end abutment fixed dental prostheses found that the magnitude of the chewing force decreased with decreasing periodontal ligament area.[118] Understanding bite force measurements prior to and during different evaluative phases over the lifespan of the patient treatment could offer the clinician additional valuable data to diagnose adverse periodontal conditions occurring around a prosthesis.

Regardless, the absence of these proprioceptors may contribute to the greater probability of tooth fracture after endodontic treatment. There have been a plethora of studies evaluating fracture loads of different materials utilized to restore vital and nonvital teeth.[78,82,83,85,119,120] Most recently, an in vitro study[121] investigated the influence of material properties and design parameters on the fracture behavior of five different monolithic dental crowns. The authors concluded that critical loads or bite forces propagating cracks in the crowns were associated with the material properties and preparation design parameters. This study used the worst-case scenario evaluating the maximum bite force under extreme conditions such as parafunctional or heavy contacts. It was concluded that the critical loads for crack propagation in monolithic crowns can be associated with preparation design parameters such as the thickness, cusp angle, and occlusal notch design. Accordingly, a design with a rounded notch, 70-degree cusp angle, and medium thickness (1.5 mm occlusal) appears to be an optimum combination of design parameters in terms of tooth conservation and failure resistance for most types of monolithic mater-

doi: 10.3290/j.qi.b3044939

ials. Zirconia possesses enough strength for a lower thickness (0.7 mm marginal and 1.05 mm occlusal) as well as a lower cusp angle (60 degrees). However, it is important to point out that any deviation to these preparation parameters could result in expedited crack propagation. CAD/CAM ceramic restorations require precision preparation to insure proper marginal fit and adaptation.[122] The in vitro studies do not carry the weight of the clinical situation where improper preparation, impression, and cementation would possibly accelerate the fracture rate.

Ultimately, an understanding and measurement of bite force, proper tooth preparation, occlusal schemes, and restorative options should be considered when treatment planning and restoring a compromised dentition because of increased risk of fracture, especially in endodontically treated and nonvital restored teeth due to diminished proprioceptor protection.

Conclusion

A standardized method to measure maximum bite force pre- and posttreatment as well as an analysis of oral habits and conditions would offer clinicians and researchers a definitive risk assessment tool to verify the contribution of variable bite forces to failures with implant- and tooth-supported prostheses. Understanding a patient's bite force would help the clinician to obtain a more complete assessment of their oral health. Along with occlusal schemes, parafunctional habits, and other patient-specific characteristics, the clinician can plan the restoration using material selection and the necessary tooth preparation parameters for direct and indirect restorations. The clinician can also guide the patient to understanding the importance of compliance with dietary restrictions and appliances for controlling parafunctional habits.

Future work

It is the authors' opinion that more information should be obtained by investigators about study subjects' oral habits and conditions prior to clinical trial commencement, including, but not limited to:

- occlusal loading analysis – frequency, localization, and/or magnitude of bite force
- parafunctional analysis – clinical assessment, questionnaire, and/or EMG for habits such as sleep bruxism
- occlusal classification analysis – Angle classification from ANB angle or "Wits" appraisal
- the role of medications, Botox, as well as dietary and behavioral changes in modifying extreme bite forces and its effect on tooth, implant, and restoration longevity in compromised clinical situations.

The findings from these additional data sets could yield insights into ways to limit dental complications or elaborate on the mechanical etiology of restoration failures.

Acknowledgments

The authors are grateful for the valuable discussion and assistance of Christopher Sitaras and Frederik Marcil for consulting on engineering principals and theories.

Disclosure

No potential conflict of interest is reported by the authors. The authors received no financial support in the research of this review.

References

1. Davies S, Gray RMJ. What is occlusion? Br Dent J 2001;191:235–245.
2. Koc D, Dogan A, Bek B. Bite force and influential factors on bite force measurements: a literature review. Eur J Dent 2010;4:223–232.
3. Nishigawa K, Bando E, Nakano M. Quantitative study of bite force during sleep associated bruxism. J Oral Rehabil 2001;28:485–491.
4. Flanagan D. Bite force and dental implant treatment: a short review. Med Devices 2017;10:141–148.
5. Misch CE. Age-related tooth loss. In: Dental Implant Prosthetics. Amsterdam: Elsevier, 2014:1–17.
6. Teixeira FB, Pereira Fernandes L de M, Tavares Noronha PA, et al. Masticatory deficiency as a risk factor for cognitive dysfunction. Int J Med Sci 2014;11:209–214.
7. Röhrle O, Saini H, Ackland DC. Occlusal loading during biting from an experimental and simulation point of view. Dent Mater 2017;34:58–68.
8. Lundgren D, Laurell L. Occlusal forces in prosthetically restored dentitions: a methodological study. J Oral Rehabil 1984;11:29–37.
9. Hattori Y, Satoh C, Kunieda T, Endoh R, Hisamatsu H, Watanabe M. Bite forces and their resultants during forceful intercuspal clenching in humans. J Biomech 2009;42:1533–1538.
10. Bakke M. Mandibular elevator muscles: physiology, action, and effect of dental occlusion. Eur J Oral Sci 1993;101:314–331.
11. Edmonds HM, Glowacka H. The ontogeny of maximum bite force in humans. J Anat 2020; 237:529–542.
12. Marcé-Nogué J, Püschel TA, Kaiser TM. A biomechanical approach to understand the ecomorphological relationship between primate mandibles and diet. Sci Rep 2017;7:1–12.
13. Bakke M. Bite force and occlusion. Semin Orthod 2006;12:120–126.
14. Turkistani KA, Alkayyal MA, Abbassy MA, et al. Comparison of occlusal bite force distribution in subjects with different occlusal characteristics. J Craniomandib Sleep Pract 2020;7:65–70.

15. Roldan SI, Restrepo LG, Isaza JF, Vélez LG, Buschang PH. Are maximum bite forces of subjects 7 to 17 years of age related to malocclusion ? Angle Orthod 2016;86:456–461.
16. Frost HM. From Wolff's law to the Utah paradigm: Insights about bone physiology and its clinical applications. Anat Rec 2001;262:398–419.
17. Matsuzaki T, Matsushita Y, Koyano K. Overload and complication of dental implant treatment. Ann Japan Prosthodont Soc 2015;7: 305–313.
18. Delgado-Ruiz RA, Calvo-Guirado JL, Romanos GE. Effects of occlusal forces on the peri-implant-bone interface stability. Periodontol 2000 2019;81:179–193.
19. Isidor F. Influence of forces on peri-implant bone. Clin Oral Implants Res 2006;17:8–18.
20. Chang M, Chronopoulos V, Mattheos N. Impact of excessive occlusal load on successfully-osseointegrated dental implants: a literature review. J Investig Clin Dent 2013;4:142–150.
21. Sadowsky SJ. Occlusal overload with dental implants: a review. Int J Implant Dent 2019;5:1–5.
22. Janovic A, Saveljic I, Vukicevic A, et al. Occlusal load distribution through the cortical and trabecular bone of the human mid-facial skeleton in natural dentition: A three-dimensional finite element study. Ann Anat 2015;197:16–23.
23. Canger EM, Çelenk P. Radiographic evaluation of alveolar ridge heights of dentate and edentulous patients. Gerodontology 2012;29: 17–23.
24. Haraldson T, Karlsson U, Carlsson GE. Bite force and oral function in complete denture wearers. J Oral Rehabil 1979;6:41–48.
25. Bhoyar PS, Godbole SR, Thombare RU, P akhan AJ. Effect of complete edentulism on masseter muscle thickness and changes after complete denture rehabilitation: an ultrasonographic study. J Investig Clin Dent 2012;3:45–50.
26. Ozturk CN, Ozturk C, Bozkurt M, Uygur HS, Papay FA, Zins JE. Dentition, bone loss, and the aging of the mandible. Aesthetic Surg J 2013;33: 967–974.
27. Tallgren A. The continuing reduction of the residual alveolar ridges in complete denture wearers: A mixed-longitudinal study covering 25 years. J Prosthet Dent 1972;27:120–132.
28. Lindquist LW, Carlsson GE, Jemt T. A prospective 15-year follow-up study of mandibular fixed prostheses supported by osseointegrated implants: Clinical results and marginal bone loss. Clin Oral Implants Res 1996;7:329–336.
29. Zimmermann J, Sommer M, Grize L, Stubinger S. Marginal bone loss 1 year after implantation: A systematic review for fixed and removable restorations. Clin Cosmet Investig Dent 2019;11:195–218.
30. Helkimo E, Carlsson GE, Helkimo M. Bite force and state dentition. Acta Odont Scand 1976;35:297–303.
31. Zivko-Babic J, Panduric J, Jerolimov V, Mioc M, Pizeta L, Jakovac M. Bite force in subjects with complete dentition. Coll Antropol 2002; 26:293–302.
32. Braun S, Bantleon H-P, Hnat WP, Freudenthaler JW, Marcotte MR, Johnson BE. A study of bite force, part 1: Relationship to various physical characteristics. Angle Orthod 1995;65:367–372.
33. Waltimo A, Könönen M. A novel bite force recorder and maximal isometric bite force values for healthy young adults. Eur J Oral Sci 1993;101:171–175.
34. Hidaka O, Iwasaki M, Saito M, Morimoto T. Influence of clenching intensity on bite force balance, occlusal contact area, and average bite pressure. J Dent Res 1999;78:1336–1344.
35. Kumagai H, Suzuki T, Hamada T, Sondang P, Fujitani M, Nikawa H. Occlusal force distribution on the dental arch during various levels of clenching. J Oral Rehabil 1999;26:932–935.
36. Shinogaya T, Bakke M, Thomsen CE, Vilmann A, Sodeyama A, Matsumoto M. Effects of ethnicity, gender and age on clenching force and load distribution. Clin Oral Investig 2001;5:63–68.
37. Varga S, Spalj S, Lapter Varga M, Anic Milosevic S, Mestrovic S, Slaj M. Maximum voluntary molar bite force in subjects with normal occlusion. Eur J Orthod 2011;33:427–433.
38. Serra CM, Manns AE. Bite force measurements with hard and soft bite surfaces. J Oral Rehabil 2013;40:563–568.
39. Bakke M, Holm B, Jensen BL, Michler L, Möller E. Unilateral, isometric bite force in 8–68-year-old women and men related to occlusal factors. Eur J Oral Sci 1990;98:149–158.
40. Kleinfelder JW, Ludwig K. Maximal bite force in patients with and without splinting. J Periodontol 2002;73:1184–1187.
41. Ferrario VF, Sforza C, Serrao G, Dellavia C, Tartaglia GM. Single tooth bite forces in healthy young adults. J Oral Rehabil 2004;31:18–22.
42. Van Der Bilt A, Tekamp A, Van Der Glas H, Abbink J. Bite force and electromyograpy during maximum unilateral and bilateral clenching. Eur J Oral Sci 2008;116:217–222.
43. Lepley CR, Throckmorton GS, Ceen RF, et al. Relative contributions of occlusion, maximum bite force, and chewing cycle kinematics to masticatory performance. Am J Orthod Dentofac Orthop 2011;139:606–613.
44. Amid R, Ebrahimi N, Kadkhodazadeh M, et al. Clinical evaluation of a new device to measure maximum bite force. Dent Case Rep 2018;2:26–29.
45. Khan SIR, Rao D, Ramachandran A, Ashok BV. Comparison of bite force on the dominant and nondominant sides of patients with habitual unilateral chewing: A pilot study. Gen Dent 2020;68:60–63.
46. Takaki P, Vieira M, Bommarito S. Maximum bite force analysis in different age groups. Int Arch Otorhinolaryngol 2014;18:272–276.
47. Poli O, Manzon L, Niglio T, Ettorre E, Vozza I. Masticatory force in relation with age in subjects with full permanent dentition: a cross-sectional study. Healthcare 2021;9:700.
48. Callister Jr WD, Rethwisch DG. An Introduction: Material Science and Engineering. 8th ed. New York: John Wiley & Sons, 2009.
49. Kosaka T, Ono T, Kida M, et al. A prediction model of masticatory performance change in 50- to 70-year-old Japanese: The Suita study. J Dent 2021;104:103535.
50. Bakke M, Michler L, Möller E. Occlusal control of mandibular elevator muscles. Eur J Oral Sci 1992;100:284–291.
51. Shinogaya T, Sodeyama A, Matsumoto M. Bite force and occlusal load distribution in normal complete dentitions of young adults. Eur J Prosthodont Restor Dent 1999;7:65–70.
52. Raj R, Koli DK, Bhalla AS, Jain V, Manchanda S, Nanda A. Effect of rehabilitation by using the shortened dental arch concept on the thickness of the masseter muscle and occlusal force: A pilot study (Epub ahead of print, 15 Jan 2022). J Prosthet Dent doi: 10.1016/j.prosdent.2021.12.009.
53. Flanagan D, Fisher A, Ciardiello C, et al. A theoretical iteration for predicting the feasibility for immediate functional dental implant loading. J Oral Implantol 2021;47:310–317.
54. Flanagan D. Diet and implant complications. J Oral Implantol 2016;42:305–310.
55. Tortopidis D, Lyons MF, Baxendale RH, Gilmour WH. The variability of bite force measurement between sessions, in different positions within the dental arch. J Oral Rehabil 1998;25:681–686.
56. Koc D, Dogan A, Bek B, Yucel M. Effects of increasing the jaw opening on the maximum bite force and electromyographic activities of jaw muscles. J Dent Sci 2012;7:14–19.
57. Awawdeh L, Hemaidat K, Al-Omari W. Higher maximal occlusal bite force in endodontically treated teeth versus vital contralateral counterparts. J Endod 2017;43:871–875.
58. Verma TP, Kumathalli KI, Jain V, et al. Bite force recording devices: a review. J Clin Diagnostic Res 2017;11:ZE01–ZE05.
59. Fernandes CP, Glantz POJ, Svensson SA, Bergmark A. A novel sensor for bite force determinations. Dent Mater 2003;19:118–126.
60. Mitchem JA, Katona TR, Moser EAS. Does the presence of an occlusal indicator product affect the contact forces between full dentitions? J Oral Rehabil 2017;44:791–799.
61. Tekscan. T-Scan Novus | Occlusal Analysis System | Tekscan. https://www.tekscan.com/products-solutions/systems/t-scan-novus. 2014. Accessed 12 Apr 2021.
62. Cerna M, Ferreira R, Zaror C, et al. Validity and reliability of the T-Scan III for measuring force under laboratory conditions. J Oral Rehabil 2015;42:544–551.
63. Kube Innovation Inc. Discover the Innobyte. http://www.kubeinnovation.com. 2020. Accessed 4 Jan 2021.
64. Fields HW, Proffit WR, Case JC, Vig KW. Variables affecting measurements of vertical occlusal force. J Dent Res 1986;65:135–138.
65. Terebesi S, Giannakopoulos NN, Brüstle F, et al. Small vertical changes in jaw relation affect motor unit recruitment in the masseter. J Oral Rehabil 2016;43:259–268.
66. Jain S, Gupta A, Jain D. Estimation of sample size in dental research. Int Dent Med J Adv Res 2015;1:1–6.
67. Boven GC, Raghoebar GM, Vissink A, Meijer HJ. Improving masticatory performance, bite force, nutritional state and patient's satisfaction with implant overdentures : a systematic review of the literature. J Oral Rehabil 2014;42:220–233.
68. Limpuangthip N, Somkotra T, Arksornnukit M. Subjective and objective measures for evaluating masticatory ability and associating factors of complete denture wearers: A clinical study. J Prosthet Dent 2020;125:287–293.
69. Possebon AP da R, Schuster AJ, Bielemann AM, Porto BL, Boscato N, Faot F. Evaluation of bite force and masticatory performance: complete denture vs mandibular overdenture users. Braz Dent J 2020;31:399–403.

doi: 10.3290/j.qi.b3044939

70. Vo TL, Kanazawa M, Myat K, et al. Masticatory function and bite force of mandibular single-implant overdentures and complete dentures : a randomized crossover control study. J Prosthodont Res 2019;63:428–433.

71. Misch CE, Suzuki JB, Misch-Dietsh FM, et al. A positive correlation between occlusal trauma and peri-implant bone loss: Literature support. Implant Dent 2005;14:108–116.

72. Marcelo CG, Filié Haddad M, Gennari Filho H, Marcelo Ribeiro Villa L, Dos Santos DM, Aldiéris AP. Dental implant fractures – aetiology, treatment and case report. J Clin Diagnostic Res 2014;8:300–304.

73. Esquivel-Upshaw JF, Mehler A, Clark AE, Neal D, Anusavice KJ. Fracture analysis of randomized implant-supported fixed dental prostheses. J Dent 2014;42:1335–1342.

74. McDermott NE, Chuang NE, Woo VV, Dodson TB. Complications of dental implants: identification, frequency, and associated risk factors. Int J Oral Maxillofac Implants 2003;18:848–855.

75. Kumararama SS, Chowdhary R. Selection of dental implants based on masticatory load of the patient: a novel approach. Indian J Dent Res 2017;28:309–313.

76. Demenko V, Linetskiy I, Nesvit K, Shevchenko A. Ultimate masticatory force as a criterion in implant selection. J Dent Res 2011;90:1211–1215.

77. Stoichkov B, Kirov D. Analysis of the causes of dental implant fracture: A retrospective clinical study. Quintessence Int 2018;49:279–286.

78. Zhang Y, Sailer I, Lawn BR. Fatigue of dental ceramics. J Dent 2013;41:1135–1147.

79. Sakka S, Baroudi K, Nassani MZ. Factors associated with early and late failure of dental implants. J Investig Clin Dent 2012;3:258–261.

80. Lipski T, Kijak E, Witaszek K, et al. Application of electronic dental dynamometer in biomechanics. J Meas Eng 2015;3:17–22.

81. Van Nieuwenhuysen JP, D'Hoore W, Carvalho J, Qvist V. Long-term evaluation of extensive restorations in permanent teeth. J Dent 2003;31:395–405.

82. Choi S, Yoon HI, Park EJ. Load-bearing capacity of various CAD/CAM monolithic molar crowns under recommended occlusal thickness and reduced occlusal thickness conditions. J Adv Prosthodont 2017;9:423–431.

83. Preis V, Hahnel S, Behr M, Bein L, Rosentritt M. In-vitro fatigue and fracture testing of CAD/CAM-materials in implant-supported molar crowns. Dent Mater 2017;33:427–433.

84. Hasan I, Bourauel C, Mundt T, Stark H, Heinemann F. Biomechanics and load resistance of small-diameter and mini dental implants: a review of literature. Biomed Tech (Berl) 2014;59:1–5.

85. Schultheis S, Strub JR, Gerds TA, Guess PC. Monolithic and bi-layer CAD/CAM lithium-disilicate versus metal-ceramic fixed dental prostheses: Comparison of fracture loads and failure modes after fatigue. Clin Oral Investig 2013;17:1407–1413.

86. Badr RM Al, Hassan HA. Effect of immersion in different media on the mechanical properties of dental composite resins. Int J Appl Dent Sci 2017;3:81–88.

87. Zhang Y, Song JK, Lawn BR. Deep-penetrating conical cracks in brittle layers from hydraulic cyclic contact. J Biomed Mater Res B Appl Biomater 2005;73:186–193.

88. Salazar Marocho SM, Studart AR, Bottino MA, Bona AD. Mechanical strength and subcritical crack growth under wet cyclic loading of glass-infiltrated dental ceramics. Dent Mater 2010;26:483–490.

89. Shemtov-Yona K, Rittel D, Levin L, Machtei EE. The effect of oral-like environment on dental implants' fatigue performance. Clin Oral Implants Res 2014;25:166–170.

90. Angwarawong T, Reeponmaha T, Angwaravong O. Influence of thermomechanical aging on marginal gap of CAD-CAM and conventional interim restorations. J Prosthet Dent 2020;124:566.e1–566.e6.

91. Yang R, Arola D, Han Z, Zhang X. A comparison of the fracture resistance of three machinable ceramics after thermal and mechanical fatigue. J Prosthet Dent 2014;112:878–885.

92. Bergamo ETP, Campos TMB, Lopes ACO, et al. Hydrothermal aging affects the three-dimensional fit and fatigue lifetime of zirconia abutments. J Mech Behav Biomed Mater 2021;124:104832.

93. Selwitz RH, Ismail AI, Pitts NB. Dental caries. Lancet 2007;369:51–59.

94. Saini H, Ackland DC, Gong L, Cheng, Röhrle O. Occlusal load modelling significantly impacts the predicted tooth stress response during biting: a simulation study. Comput Methods Biomech Biomed Engin 2020;23:261–270.

95. Scherrer SS, Mekki M, Crottaz C, et al. Translational research on clinically failed zirconia implants. Dent Mater 2018;35:368–388.

96. Raabe D, Harrison AJL, Ireland AJ, et al. Improved single- and multi-contact life-time testing of dental restorative materials using key characteristics of the human masticatory system and a force / position-controlled robotic dental wear simulator. Bioinspir Biomim 2012;7:016002.

97. Choi AH, Matinlinna JP, Ben-nissan B. Finite element stress analysis of Ti-6Al-4V and partially stabilized zirconia dental implant during clenching. Acta Odontol Scand 2012;70:353–361.

98. Yoshitani M, Takayama Y, Yokoyama A. Significance of mandibular molar replacement with a dental implant: a theoretical study with nonlinear finite element analysis. Int J Implant Dent 2018;4:4–13.

99. Jansen van Vuuren L, Broadbent JM, Duncan WJ, et al. Maximum voluntary bite force, occlusal contact points and associated stresses on posterior teeth. J R Soc New Zeal 2020;50:132–143.

100. Teja S, Teja P. All-ceramic materials in dentistry. Saint Int Dent J 2015;1:91.

101. Rosentritt M, Preis V, Behr M, Strasser T. Fatigue and wear behaviour of zirconia materials. J Mech Behav Biomed Mater 2020;110:103970.

102. Li W, Xu Y, He H, Zhao H, Sun J, Hou Y. Strength degradation and lifetime prediction of dental zirconia ceramics under cyclic normal loading. Biomed Mater Eng 2015;26:S129–S137.

103. Borgard H. Predicting occlusal force and area through a biomechanical simulation of mastication and controlled study [Thesis]. Vancouver: University of British Columbia, 2020.

104. Akano TT. Fatigue life of the human teeth: A continuum damage approach. J Biomim Biomater Biomed Eng 2019;43:1–19.

105. Nalla RK, Imbeni V, Kinney JH, Staninec M, Marshall SJ, Ritchie RO. In vitro fatigue behavior of human dentin with implications for life prediction. J Biomed Mater Res A 2003;66:10–20.

106. Scherrer SS, Lohbauer U, Della A, et al. ADM guidance — Ceramics : guidance to the use of fractography in failure analysis of brittle materials. Dent Mater 2017;33:599–620.

107. Kruzic JJ, Arsecularatne JA, Tanaka CB, Hoffman MJ, Cesar PF. Recent advances in understanding the fatigue and wear behavior of dental composites and ceramics. J Mech Behav Biomed Mater 2018;88:504–533.

108. Miura S, Yamauchi S, Kasahara S, Katsuda Y, Fujisawa M, Egusa H. Clinical evaluation of monolithic zirconia crowns: a failure analysis of clinically obtained cases from a 3.5-year study. J Prosthodont Res 2020;65:643.

109. Assif D, Gorfil C. Biomechanical considerations in restoring endodontically treated teeth. J Prosthet Dent 1994;71:565–567.

110. Van Dijken JWV, Hasselrot L. A prospective 15-year evaluation of extensive dentin-enamel-bonded pressed ceramic coverages. Dent Mater 2010;26:929–939.

111. Dong WK, Chudler EH, Martin RF. Physiological properties of intradental mechanoreceptors. Brain Res 1985;334:389–395.

112. Loewenstein WR, Rathkamp R. A study on the pressoreceptive sensibility of the tooth. J Dent Res 1955;34:287–294.

113. Alkan A, Keskiner I, Arici S, Sato S. The effect of periodontal surgery on bite force, occlusal contact area and bite pressure. J Am Dent Assoc 2006;137:978–983.

114. Williams WN, Low SB, Cooper WR, Cornell CE. The effect of periodontal bone loss on bite force discrimination. J Periodontol 1987;58:236–239.

115. Paphangkorakit J, Osborn JW. Effects on human maximum bite force of biting on a softer or harder object. Arch Oral Biol 1998;43:833–839.

116. Kim Y, Oh TJ, Misch CE, Wang HL. Occlusal considerations in implant therapy: Clinical guidelines with biomechanical rationale. Clin Oral Implants Res 2005;16:26–35.

117. Morita M, Nishi K, Kimura T, et al. Correlation between periodontal status and biting ability in Chinese adult population. J Oral Rehabil 2003;30:260–264.

118. Laurell L, Lundgren D. Periodontal ligament areas and occlusal forces in dentitions restored with cross- arch bilateral end abutment bridges. J Clin Periodontol 1985;12:850–860.

119. Zacher J, Bauer R, Strasser T, Rosentritt M. Laboratory performance and fracture resistance of CAD/CAM implant-supported tooth-coloured anterior FDPs. J Dent 2020;96:103326.

120. Zhang Y, Mai Z, Barani A, Bush M, Lawn B. Fracture-resistant monolithic dental crowns. Dent Mater 2016;32:442–449.

121. Shahmoradi M, Wan B, Zhang Z, et al. Monolithic crowns fracture analysis: The effect of material properties, cusp angle and crown thickness. Dent Mater 2020;36:1038–1051.

122. Atlas A, Isleem W, Bergler M, Fraiman HP, Walter R, Lawson ND. Factors affecting the marginal fit of CAD-CAM restorations and concepts to improve outcomes. Curr Oral Health Rep 2019;6:277–283.

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doi: 10.3290/j.qi.b3044939