Review
Biomechanics of occlusion – implications for oral rehabilitation

C. C. PECK  Faculty of Dentistry, The University of Sydney, Sydney, NSW, Australia

SUMMARY The dental occlusion is an important aspect of clinical dentistry; there are diverse functional demands ranging from highly precise tooth contacts to large crushing forces. Further, there are dogmatic, passionate and often diverging views on the relationship between the dental occlusion and various diseases and disorders including temporomandibular disorders, non-caries cervical lesions and tooth movement. This study provides an overview of the biomechanics of the masticatory system in the context of the dental occlusion’s role in function. It explores the adaptation and precision of dental occlusion, its role in bite force, jaw movement, masticatory performance and its influence on the oro-facial musculoskeletal system. Biomechanics helps us better understand the structure and function of biological systems and consequently an understanding of the forces on, and displacements of, the dental occlusion. Biomechanics provides insight into the relationships between the dentition, jaws, temporomandibular joints, and muscles. Direct measurements of tooth contacts and forces are difficult, and biomechanical models have been developed to better understand the relationship between the occlusion and function. Importantly, biomechanical research will provide knowledge to help correct clinical misperceptions and inform better patient care. The masticatory system demonstrates a remarkable ability to adapt to a changing biomechanical environment and changes to the dental occlusion or other components of the musculoskeletal system tend to be well tolerated.

KEYWORDS: dental occlusion, bite force, biomechanics, temporomandibular disorders, stomatognathic system, temporomandibular joint

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Introduction
This study outlines a presentation at the 2013 Colloquium on Oral Rehabilitation (CORE) in China, which explored the biomechanics of dental occlusion, including the structure–function relationships between the occlusion and the temporomandibular joint and jaw muscles. Further, it describes how the dental occlusion and biomechanical concepts are important in influencing adaptation of the masticatory system and how we may use this in oral rehabilitation.

The Glossary of Prosthodontic Terms defines dental occlusion as the static relationship between the incising or masticating surfaces of the maxillary or mandibular teeth or tooth analogues (1). This aligns with much of clinical practice in which assessment and description of the occlusion is of interarch tooth relationships in static jaw positions, such as in intercuspal, lateral or protrusive jaw positions. Whilst static positions are relatively easy to describe and assess, teeth contacts need to be assessed from a functional perspective and a more fitting definition of dental occlusion is the dynamic biological relationship of the components of the masticatory system that determine tooth relationships (2). Any definition needs to encompass the enormous individual variation in the human population, and it must be
emphasised that stable occlusal relationships are the norm (2).

The discipline of biomechanics enables us to better understand the dental occlusion through an understanding of structure–function relationships. Biomechanics explores the mechanical characteristics, such as forces and motion, of biological systems and utilises direct assessment when possible or, for instance, mathematical modelling to help derive the mechanical properties. For example, it is currently very difficult or impossible to measure all biomechanical variables directly such as the muscle and dental occlusal forces during normal jaw function. Furthermore, measuring devices such as force gauges and motion recorders will alter and likely influence the biological environment being studied. Take for example, gauges used between the teeth to measure bite force which increase interincisal gape and prevent normal function.

The masticatory system is functionally complex with six degrees of movement possible (i.e. movement anywhere in space described as translation along and rotation about three mutually orthogonal axes) and coactivation of sixteen jaw muscle groups resulting in complex force interactions at the teeth. This jaw system is indeterminate, and theoretically, there are infinite muscle coactivation patterns to produce a desired bite force or jaw movement. However, reproducible tooth contact movements (3) and rhythmic jaw movements are common during function with a regular motor command pattern generated in the brainstem (4).

Occlusion: a system of adaptation and precision

There are few areas in dentistry that engender the level of heated debate as does the area of dental occlusion. Whilst no one will argue about Posselt's statement that 'occlusion is a basic principle in dentistry' (5), there is limited evidence for the definition and evaluation of occlusion among dental procedures (6) and there is confusion regarding the optimal occlusal relationship (7). Reasons for this include the large variation in dental occlusions in the population, the lack of validated diagnostic criteria for many occlusal problems and the term malocclusion which suggests something is wrong even though 70% of American youths have a malocclusion (8). It is important to note that a particular occlusal scheme is not a predictor of disease, and there is significant overlap of occlusal features between individuals with and without jaw disorders (9, 10). Indeed, the diversity in occlusal patterns in populations has likely increased markedly with the advent of farming and industrialisation and consequent reduction in selective pressures that cause genetic adaptation (11). Studies of Australian Aboriginal populations who lived traditionally demonstrate a high frequency of bimaxillary protrusion, significant occlusal and interproximal tooth wear and balanced occlusion (bilateral posterior dental contacts during lateral movement, 1) and group function (multiple tooth contacts on the working side during lateral jaw movement, 1) which are related largely to functional demands (12). More recent changes are demonstrated in Finland where occlusal schemes have been compared over the past 400 years (13). In the 17th century, distal bites, deep bites, posterior cross-bites and maxillary crowding occurred in less than 5% of a Finnish community; this has increased to prevalences of between 15 and 25% in the 1950s, reportedly as a result to changing functional demands, viz. the dietary transition from hard to soft food. These occlusal changes, exemplified above in Australian Aboriginal and Finnish populations, are likely a result of continual adaptation to functional demands. Indeed, anterior guided occlusions, which currently predominate in many societies, were likely present in these earlier societies as a transient phase during an individual's development (14). Furthermore, whilst there is no evidence to suggest one occlusal scheme predominates over another (15), it has been suggested that in oral rehabilitation, canine guidance is frequently favoured over group function (16), and this is likely because of its relative ease in design and fabrication and relatively lower muscle activity and consequently lower forces on the dentition (16). Another frequent structure–function relationship encountered relates to the orientation of the dentition; the Curves of Spee and of Wilson (1). They are likely formed to ensure teeth are aligned parallel to jaw-closing forces so that the forces are transmitted along the tooth axis and thus minimise any damage to the dentition and periodontium. As well, the occlusal scheme can influence muscle structure by altering mitochondrial content, cross-sectional area of muscle fibres, fibre-type composition jaw-closing muscle size and ultimately may enhance masticatory ability (17).
Occlusal perception is great, with most individuals being able to detect thicknesses of 10–35 μm between the teeth (18). Furthermore, we are able to precisely grasp and position a food bolus between our teeth and the forces needed for this are largely regulated by periodontal mechanoreceptors (19). These receptors are particularly sensitive for such light ‘holding’ forces and demonstrate highest sensitivity for forces below 1 Newton applied to the anterior teeth and 4 Newtons for the posterior teeth (20). Loss of periodontal attachment, dental anaesthesia and dental implants all impair this functional ability (19, 21–24). Conversely, it may be expected that disturbance of the periodontium (e.g. trauma) could result in a persistent sensitisation of the periodontal mechanoreceptors and a heightened occlusal awareness. Importantly, such phenomena may be influenced by psychological and social aspects as is the case with sensitisation and chronic pain (25).

Occlusion and bite force

Today, a functional dental occlusion is required primarily for mastication by providing the ‘tools’ within the masticatory system through which to apply muscle forces to incise and comminute foods. Whilst the teeth can be used for other tasks such as prehension or as weapons, this is not the norm in modern human society. Bite forces are generated by the coactivation of predominantly the masseter, medial pterygoid and temporalis muscles (the primary jaw closer muscles). These jaw closer muscles’ potential force generation is related to their cross-sectional size and muscle length (27). A muscle can generate in the order of 37 N cm\(^{-2}\) at its optimal length which lies somewhere between a shortened and fully extended muscle (27). For the jaw closer muscles, this optimal length lies at a position between jaw closed and wide gape positions, and for each of the closer muscles, this optimal position is not necessarily at the same gape. Consequently, when all jaw closer muscles’ optimal length are considered, humans can generate maximum closing force not with the teeth intercuspating, but at two gapes: an interincisal gape at approximately 20 mm and again at 40 mm (28).

The modern occlusal pattern is largely dictated by the forces applied to the jaw system. Whilst bite forces tend to be predominantly aligned vertically and parallel with the long axis of the teeth, with grinding of foods, there are sheering forces between the teeth with forces directed laterally and/or anteroposteriorly. To measure these is not trivial as sensors need to be able to detect such three dimensional forces and not interfere with the dental occlusion or function. Methods have been developed for this in the research setting; for example, telemetry has been used with an eight-channel force transmitter in a removable fixed partial denture (29). However, simple bite force gauges are commonly used in which typically uniaxial vertical forces are measured between pairs of opposing teeth or across the whole dental arch with pressure-sensitive sheets that cover all teeth (30). Of note is that these tools may influence bite force as they increase the occlusal vertical dimension, the closing muscle lengths and consequently their muscle tensions. Further, bite force depends on a subject’s cooperation and motivation. Notwithstanding these limitations, simple bite force instruments provide a quick method of measuring interocclusal forces to assess the functional state of the masticatory system and loading on the teeth (30).

Force levels vary greatly between individuals with full-arch maximum force measurements varying between 600N and 1200N (31) and anterior teeth maximum bite forces only reaching 20% of this level (30). Functional forces during mastication and swallowing are relatively high at approximately 40% of maximum bite force (32). The large variation in bite force can be accounted for by a number of variables including subject motivation and cooperation, jaw muscle size, presence of pain (correlated with lower bite force), jaw gape (see above), age (maximum during 20–40 years), sex (males with greater muscle size and fibre differences) and craniofacial morphology (long face individuals generate up to half the bite force of square face individuals) (30).

Whilst there is significant correlation between bite force and number of teeth (33), the number of tooth contacts is a stronger determinant of bite force level (34). Approximately 80% of the total bite force is distributed across the molar teeth (35), and simple mechanics of bite point proximity to the muscle force helps explain larger bite forces on the molars than anterior teeth (31). In addition, biomechanical analyses demonstrate the combined moment produced by the jaw muscles was the largest for vertical bites, the smallest for posteriorly directed bites and intermediate for anteriorly directed bites (36). This may suggest that any planning for occlusal modification by
orthodontics or oral rehabilitation should focus on tooth contacts which facilitate vertically directed occlusal forces.

Occlusal forces have been implicated in the development and progression of abfraction lesions, and wedge-shaped defects at the cervical region of teeth (37). Biomechanical studies suggest non-axial loading of teeth leads to stress concentration at the cervical region and possibly fracture and loss of tooth structure (38). Whilst there are associations between occlusal loading scenarios such as wear facets, bruxism and premature tooth contacts, this does not confirm any causal relationship. Interestingly, abfraction lesions have not been reported in pre-contemporary populations (11), and it is suggested there is multifactorial aetiology to these lesions and that occlusal adjustments or other irreversible treatments be avoided (11, 37).

Adaptation is the norm with changes to dental occlusal forces. Changing functional loads in an animal model demonstrate adaptive changes to the periodontium including alterations to periodontal ligament orientation, periodontal ligament turnover rate, apical cementum resorption, mineral composition, and alveolar bone and secondary cementum hardness (39, 40). These multiple effects help explain the overall biomechanical effects of altered loading and are important when trying to understand when the adaptive capacity is exceeded particularly with dental (e.g. orthodontics, prosthodontics) or disease (e.g. periodontal disease) influences (41, 42).

Occlusion and jaw movement

Jaw movement has been studied extensively at the occlusal interface, with Ulf Posselt being one of the first to describe it accurately in three dimensions (43). The horizontal range of movement (i.e. occlusal paths) of the incisor and molar teeth is similar, but vertical range is markedly different with the incisor teeth movement greater than that at the molar (44). The occlusal paths are, by definition, dictated by anterior determinants such as anterior dental overbite and other tooth contact relationships and the posterior determinants such as the condylar guidance of the temporomandibular joints (45). From a biomechanical perspective, the anterior determinants, compared to posterior determinants, will have a greater influence on tooth contact patterns because of their proximity to the teeth. For example, consider a deep anterior dental overbite (anterior determinant) which will likely cause posterior dental discusion in protrusive or lateral jaw movements. Condylar guidance will influence tooth contacts in cases where molar teeth contact, or are close to contact, during jaw movements (45). It is important in such clinical cases to assess carefully tooth contacts and measurements for posterior dental articulator settings to minimise the risk of introducing occlusal interferences during oral rehabilitation. These occlusal and temporomandibular joint relationships are expected as the mandible, in this context, is a rigid body, and movement at one point (e.g. tooth) will be related to another point (e.g. condyle).

As outlined above, occlusal perception is in the order of tens of microns and individual tooth movement in function is approximately 100 microns (44). Tooth movement is not unidimensional and thus for accurate assessment, one needs to measure the movement in three dimensional space. There is instrumentation available to measure with this accuracy and precision and this in turn could lead to the development of complex occlusal assessment tools that utilise high precision jaw and tooth movement data and have resolution in the order of microns (44). Whilst work in this area is currently in the research domain, such tools could be particularly useful in patients with very acute occlusal perception.

Occlusion and masticatory performance

One must place the role of the dental occlusion in jaw function into context. In normal function, teeth contact during mastication and swallowing. During mastication, approximately only 20% of the time is spent with possible tooth contacts and this varies with the consistency of foods, and harder foods resulted in less tooth contact. The total duration of this contact is in the vicinity of 10–20 min daily, and as such, the pathogenicity of occlusal imbalance and malfunction due to tooth contact during mastication should be disputed (46).

A functional dental occlusion is important for general health, and masticatory performance (as determined by breakdown of food) is closely correlated with occlusal contact area, with larger contact areas in those subjects demonstrating better performance (47). The loss of teeth leads to reduced ability to comminute foods and has been associated with reduced
intake of fruits and vegetables and lower systemic biochemical levels, nutrients and dietary fibre and increased gastritis, diabetes and obesity (48).

A World Health Organization workshop held in 1982 on community oral health services concluded a goal for oral health is ‘the retention throughout life of a functional, aesthetic, natural dentition of not less than 20 teeth and not requiring recourse to a prosthesis’ (49). Masticatory ability closely correlates with the number of teeth and is impaired when there are fewer than 20 uniformly distributed teeth in the mouth (50). Whilst a full complement of occluding teeth is preferable, the shortened dental arch scenario, comprising the anterior and premolar regions, meets the requirements of a functional dentition (51). Any reported difficulty of mastication is inversely related to the number of pairs of occluding teeth, and masticatory ability is maintained if the premolar regions are intact and there is at least one pair of occluding molars. Masticatory ability is severely impaired, particularly in comminuting hard foods, with fewer occluding premolars and/or asymmetric arches/unevenly distributed teeth (52). Impaired masticatory ability and resulting changes in the types of foods selected tend to occur only when there are less than 10 pairs of occluding teeth (53). In shortened dental arches, occlusal contacts tend to change, with distal tooth migration resulting in increased anterior dentition load and contacts. These structural and functional adaptations tend to stabilize maintaining satisfactory oral function (54).

Whilst the biomechanical environment changes with a change to a shortened dental arch, it appears to be one of adaptation and not pathology. Despite a greater prevalence of joint sounds, there are no differences in pain, mandibular mobility, maximum mouth opening, or articular crepitus between shortened and full dental arch scenarios (55, 56). To explore the biomechanical consequences of shortened dental arches, a finite element model of the jaw has been developed and validated with human bite force data. The model calculates data that cannot be readily obtained in vivo including muscle, joint and periodontal forces for different occlusal scenarios in which posterior teeth were sequentially ‘removed’ (57). The tooth contacts influenced these forces in the masticatory system; when molar contacts were removed, the overall bite force decreased, bite force on each tooth increased and the force always remained greatest on the most posterior tooth. Joint loads decreased with missing molar occlusal contact and periodontal loading on the most distal tooth remained reasonably constant irrespective of number of occluding posterior teeth. This modelling suggests the masticatory system adapts to structural changes of the dental occlusion and protects the temporomandibular joints and dentition by regulating their loads by adjusting muscle activity patterns. The shortened dental arch comprising the anterior and premolar regions appears to ensure good oral function and patient comfort and suggests extensive oral rehabilitation to regain a full complement of occluding teeth is not always necessary.

**Occlusion and the musculoskeletal system**

From a clinical perspective, changes to the temporomandibular joint including intracapsular exudate and loss of articular tissue may result in occlusal changes such as anterior or posterior open bites (58). Conversely, occlusal changes can result in articular changes such as altered movement paths. Experimentally altering occlusal contacts results in condylar movement and position changes. The addition of a working side interference resulted in more anteroinferior working condyle movement (59) and balancing side occlusal contacts appear to reduce balancing side condylar displacement (60). Compared to canine guided occlusions, simulated group function occlusion caused smaller working side condylar displacement and simulated bilateral balanced occlusion caused significantly smaller non-working side and working side condylar displacements (61). These condylar displacement changes are small and, in isolation, may have no clinical significance. Further research is warranted to determine whether or not such changes together with other factors (e.g. condylar loading) contribute to scenarios that exceed the adaptive potential of the system (e.g. osteoarthritis).

There has been much mathematical modelling of the masticatory system to understand better structure–function relationships. The simplest, static mathematical modelling suggests that in the sagittal plane (where occlusal contacts and muscle activity are assumed the same on left and right sides of the jaw), there is no alterations to the dental occlusion which will result in ‘unloading’ of the joint, a clinical desirable outcome with an inflamed joint. The reason for this is that because the closing muscle forces are
always posterior to any occlusal contacts (62), the jaw acts as a lever with the condyle as a fulcrum. The consequence is that with any tooth contact scheme, there will always be compressive condylar forces. This modelling refutes the ‘condylar unloading’ premise of oral appliances which provide only molar contacts about which the jaw pivots and ‘distracts’ the condyle. Note that this modelling is two dimensional and it is likely possible to cause differential condylar loading with only unilateral bite points. Differential condylar loading would depend on bite point and working and balancing side muscle activities (62). Nevertheless, it is important to consider what scenarios reduced condylar loading may be warranted and these may include acute arthralgia and arthritis. If reduced condylar loading is warranted, then other management strategies such as reducing function and other behavioural strategies rather than dental occlusal modification should be considered.

Dynamic jaw models provide opportunity to assess scenarios with changing jaw muscle activities or jaw motions and have the advantage of assessing the masticatory system whilst simulating function. A dynamic mathematical model of the jaw which includes a rigid mandible, 16 force vectors representing the masticatory muscles, multiple occlusal contacts and curvilinear disc/fossa boundaries representing the temporomandibular joints has been used to explore different occlusal schemes and their effects on temporomandibular joint force magnitude and direction (63). Balanced molar contact (Angle’s Class II molar relationship), anterior open bite, unilateral crossbite and missing posterior teeth scenarios were investigated as these have demonstrated associations (albeit low) with temporomandibular disorders (64). The model simulates a dynamic clenching task in which the jaw elevators are maximally activated linearly in time. Individual teeth were rigid and, to represent periodontal influence, could displace within the mandible and maxilla. In the balanced molar occlusal support case, in which molar teeth on both sides of the dental arch made contact evenly during the clenching task, dental contacts commence anteriorly with posterior coupling as muscle activity is increased. The joint reaction force is initially posteriorly directed but rotates forwards as clenching increases (Fig. 1). In the anterior open bite case, the forces generated at the TMJ are more posterior at the commencement of the task and with increasing elevator activity remain more posteriorly directed than the balanced molar support case. The unilateral cross-bite case demonstrates similar condylar force directions but of greater magnitude when compared to the balanced molar case. The missing posterior teeth model generates much higher condylar forces than the balanced occlusal case. Modelling has limitations as there are assumptions particularly when biological data are needed, but not available, to construct the model. Nevertheless, they provide insight into structure–function relationships which is not possible any other way. It is to be expected that movement changes at one site of the mandible will influence other sites and these experiments suggest altering the dental occlusion may change condylar movement and loading. Notwithstanding the limitations, these set of experiments support the case for occlusal contacts in both the anterior and posterior segments (at a minimum rehabilitate an individual to a shortened dental arch) and the need for evenly distributed contacting teeth.

There is evidence that changes to the dental occlusion such as the introduction of occlusal interferences increases postural activity in the jaw closers, which is reversed when the occlusal interference is removed (65). In a temporomandibular disorders group, occlusal interferences increased clinical signs compared to healthy controls. In the healthy controls, no temporomandibular disorder developed and initially jaw closer muscle activity decreased but then increased as did occlusal contacts (66). It appears that healthy subjects demonstrate adaptation, whereas temporomandibular disorder subjects do not and their response may be partly explained by psychosocial factors (67). Furthermore, whilst there are data confirming some relationships between occlusion and temporomandibular disorders, it should not be overstated and the clinical implications need to be carefully considered (10).

Although many dental practitioners agree that occlusion is one of the most important factors to consider in successful patient management, there is very limited evidence for the definition and evaluation of occlusion among dental procedures (6). This is likely due in part to the lack of sensitive and specific diagnostic tests in the assessment of the dental occlusion. It is important to realise that from a biomechanical perspective dental supracontacts and an overclosed vertical dimension are the two common occlusal disorders that can impact function, and whilst an occlusal examination is important, the patient’s self-
A report of the problem is a key reason for any management (6).

Structure–function relationships in the masticatory system are important, and there is much evidence demonstrating structural changes to the dentition can alter jaw function. It must be emphasised that any changes to the biomechanical environment tend to lead to adaptation of the system (whether adaptive remodelling of structural components or of function). There are cases where the adaptive capacity of the system is exceeded and this is likely a result of multiple factors which may include not only biological but also psychosocial factors. Further research is warranted, and biomechanical modelling can play a role in this as it helps to deconstruct the system and assess individual variables. In the interim from the biomechanics evidence, one can develop clinical recommendations (Table 1).

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**Fig. 1.** Results of dynamic mathematical modelling of temporomandibular joint condylar reaction forces resulting from tooth clenching. Four dental occlusal contact scenarios were modelled: Angle class II molar occlusion (upper diagram), anterior open bite (2nd diagram), unilateral cross-bite (3rd diagram) and missing posterior teeth (bottom diagram). Teeth which made contact during clenching are shaded. Arrows represent initial (dashed) and final (solid) condylar force vector (direction and magnitude) in sagittal plane with the left side of figure posterior direction, right side anterior direction and upper side superior direction. Maximum condylar forces are noted.

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Management of occlusal problems needs to include stable bilateral tooth contacts in intercuspal position and centric relation, well-distributed contacts in maximal intercuspation, providing axially directed forces, multidirectional freedom of contact movements radiating from maximal intercuspation and no disturbing or harmful intermaxillary contacts during lateral or protrusive excursions (68). These guidelines are based on the concept put forward by Beyron in 1954 (69) and have stood the test of time.

Conclusion

The dental occlusion has enormous functional demands placed upon it, from the precise positioning of teeth and light holding forces to the generation of large bite forces. The masticatory system demonstrates a remarkable ability to adapt to a changing biomechanical environment, whether it be changes in structure or in functional demands. Biomechanics is important in understanding better the role of the occlusion in the masticatory system and how it may contribute to health and disease. The relationship between the dental occlusion and disorders is not a straightforward biomechanical issue, and consequently, it is worthwhile to heed the recommendation of Dworkin to include a biobehavioural focus in patient care (70).

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References


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Correspondence: Christopher C. Peck, Faculty of Dentistry, The University of Sydney, Sydney, NSW 2006 Australia. E-mail: dentistry.dean@sydney.edu.au

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