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The Human Masticatory System From A Biomechanical Perspective: A Review

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SUMMARY

The human masticatory system is special because apart from a larger amount of muscles than degrees of freedom its joints do not restrict its movements a priori. Therefore, each muscle is able to influence all six degrees of freedom which makes the system kinematically and mechanically indeterminate. Furthermore, its working space is principally determined by the dynamical properties of its muscles and not by passive constraints. It is concluded, that active and passive muscle tensions through occlusion and condylar surfaces are in a state of dynamical 3D equilibrium. During evolution the masticatory system assumed a number of structural elements designed to stabilize the dental arches to withstand powerful mastication forces which consist of different vectors. Moreover, the perfect correlations exist between occlusal stability and elevator muscle function, which are based on feedback mechanisms from periodontal pressoreceptors.The perfect geometry of the occlusal surfaces and dental arches jointly with well-balanced occlusion, solid proximal dental contacts and structure of the periodontal ligament guarantee physiologically acceptable distribution and compensation of the mastication forces, thus ensure long-lasting functioning of the teeth. This ideal from a functional viewpoint system may be damaged due to periodontal disease or partial dental loss. Restoration of the functional integrity of the dental arch is one of the most relevant problems in clinical dentistry. Functional equilibrium in and between the dental arches guarantee balanced functional stimulation of the masticatory apparatus and contributes to its harmonious development and maintenance.

Key words: bite force distribution, occlusion, human jaw biomechanics.

The human masticatory system is a typical example of a kinematically and mechanically indeterminate system. Two segments, the mandible and the skull, are able to move with respect to each other. These movements are guided by two mutually linked temporomandibular joints. In each joint a mandibular condyle articulates incongruently with the articular surface of the temporal bone. The articular capsule is slack. Due to this construction both joints allow for movements with six degrees of freedom [1]. Consequently, jaw movements are not limited to rotations about one or more axes defined by the joint [2]. If the joint surfaces are assumed to be undeformable and maintain contact all the time, the mandible still is able to move with four degrees of freedom. Jaw movements can be defined by the three-dimensional path traveled by the lower central incisor [3]. This can be accomplished in various ways with the system that is able to move with at least four degrees of freedom. Jaw movements are accomplished by a large number of masticatory muscles. The majority is relatively short with large attachment areas. While these muscles can be activated heterogeneously [4], each muscle is able to influence more than one degree of freedom [5]. All muscle portions together generate a resultant force and torque (six degrees of freedom) with respect to the centre of gravity of the lower jaw [6]. The distribution of the forces and torques necessary to perform any movement over the different muscle portions is not a priori established. Consequently, the masticatory system is kinematically and mechanically redundant.

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Since we are dealing with a dynamic system and since the functions of mastication, deglutition, speech, respiration and postural maintenance depend in a large measure on the movement of the mandible and its relationship to the stable cranial and facial base, knowledge of the working of the temporomandibular joint is important.The principal task of the temporomandibular joint is to enable the jaws to move. The tensions and deformations it experiences during these movements are likely to play a crucial role in the balance between function and dysfunction [7]. Displacements of the condyle along the articular surface of the skull and perpendicular to it are caused not only by the masticatory muscles and chewing loads, but also by the joint reaction force, which is the direct result of the local tensions in its cartilaginous structures. When the joint is loaded, the condyle will move more closely to the articular eminence than when it is not [8]. This dynamic balance prevents condylar surfaces from being damaged during function.

The biomechanics of the human mandible can be explained by a complex support model, where muscular forces are produced by the masticatory muscle, and reaction forces are produced by the occlusal surfaces and condyle. It is concluded, that muscular forces through occlusion and condylar surfaces are in a state of dynamical 3D equilibrium [9]. Generally, the working space of musculo-skeletal systems is defined by constraints applied through joint construction [10, 11]. The action of the muscles is generally described by a torque about one or more joints [12, 13]. In contrast, in the human masticatory system the working space is not primarily constrained by passive structures, but by limitations for force production of its muscles and the action of the muscles cannot be described by a torque about its joints. It is evident that the muscles are the dominant determinants of jaw movement. The effects of articular forces must be taken into account, especially if the joints are loaded asymmetrically. The muscles not only move the jaw but also maintain articular stability during midline movements. Passive structures, such as the ligaments, become dominant only when the jaw reaches its movement boundaries. These ligaments are assumed to prevent joint dislocation during non-midline movements [14]. The muscular forces, which during clenching act on the jaw, along with the necessary force level for chewing, also act as some kind of stabilizers of the mandibular condyles preventing dislocation and loading of nonarticular tissues.

Human jaw motion is controlled by three pairs of anatomically heterogeneous closing muscles, and at least two pairs of depressors [15, 16 and 17]. As active tensions change with the length and shortening velocity of muscles, and as passive tensions increase when muscles stretch beyond their optimal lengths, the jaw's opening and closing movements take place in an environment of constantly changing forces. Active and passive muscle tensions contribute to the jaw's resting posture. The low levels of reflex or voluntary electrical activity recorded during postural rest, and as the jaw is raised to dental contact [18, 19, and 20] imply that passive elevator-muscle forces (and perhaps other soft-tissue forces) might be principally responsible for maintaining the resting jaw at its normal 2–3 mm interincisal separation. An alternative possibility is that passive muscle tensions support the jaw at a more open position (e.g. 12 mm), with a small amount of tonic (and fluctuating) elevator postural activity being needed to raise the jaw to its normal interincisal separation in the alert individual. In this case, the jaw would be expected to fall further open during sleep or in other unconscious states. The different optimal muscle-fibre lengths required for these two possibilities would mean different patterns of passive tensions during other, more dynamic, jaw functions such as opening and chewing [21]. Moreover, the normal, resting jaw position is most likely maintained not only by passive muscle tensions, but also by low-grade, active tensions in the closing muscles of the alert individual [22]. The passive muscle-tension properties are assumed to be optimized for multiple functions. Movements of the mandible are regulated by active muscle tensions generated by contracting muscle fibres, and also by multiple passive forces. They include the jaw's inertial forces, tendon and muscle-fibre stretch tensions, damping forces, gravity (9800 mm/s^2, perpendicular to the occlusal plane), plus reaction forces at the joints, bite points and bolus. The combined effect of the active and passive muscle tensions, plus the biomechanics of the system, produce bilaterally symmetrical condylar reaction forces [23].

Active tensions of jaw closing muscles produce strains defined as maximum bite force. Masticatory force, operating upon plane with complex geometrical surface (that are occlusal surfaces of the teeth) is defined as functional bite force. Value of the bite force depends on two factors: the force of the mastication muscles and reciprocal system which controls mastication forces via pressoreceptors of the periodontal ligaments. The neuromuscular regulatory system is designed to control the biting strength so as not to exceed the critical limit of the load-bearing capacity of the periodontal tissues. The fact that the periodontal ligament and the periosteum of the alveolar bone are rich in both mechanoreceptors and nociceptors support this idea [24]. With reference to literary data may be said that regular value of the static bite force ranges from 100 to 1000 N, while dynamic or functional force ranges from 3.5 to 350 N [25].The mean maximal bite force registrations among Europeans and Americans is in the range of 600–750 N [26], while functional masticatory forces are much lower (about 60–100 N) [27].

To compensate such powerful forces nature created system of the dental arches. Intact dental arch behaves as solid functional unit. Three principal factors determine optimal distribution of occlusal force on the dental arch: proper occlusal contacts, solid proximal dental contacts and structure of the periodontal ligament [26].

Understanding the nature of occlusal contacts is important for the better diagnosis and treatment of stomatognathic diseases [28]. Occlusal equilibrium in the intercuspal position especially, is of great importance. In this position, most tooth contact occurs during mastication [29] and the jaw closing muscles are capable of exerting the maximum masticatory force [30, 31 and 32]. Definitions of an "ideal" occlusion of the teeth in clinical dentistry usually specify even, simultaneous and bilateral tooth contacts in the intercuspal position. These are assumed to provide a balanced distribution of occlusal force [33]. The number of contacts during habitual biting can vary according to the biting pressure [34]. However evenly distributed they appear to be, simultaneous tooth contacts made during habitual clenching or tooth-tapping do not necessarily mean that forces on the teeth are also distributed evenly. The dentoalveolar tissues and supporting skeleton do not form a rigid system when acted upon by the jaw muscles, and differential tooth loads are possible despite apparently "balanced" tooth contacts. The maximum forces developed between the molar teeth are larger than those between incisors [35, 36]. When recorded between isolated pairs of antagonistic teeth, these forces increase progressively in a nonlinear but monotonic manner as the bite point moves posteriorly [37, 38]. This distribution can be explained biomechanically, since the mandible functions as a class III lever, and the tension vectors produced by isometric contraction of the jaw-closing muscles lie between the mandibular condyles and the dental arch [39, 40]. To maintain static equilibrium, reaction forces produced at isolated bite points must increase progressively the closer the bite point is to the active muscle group. In addition to the lever effect, however, forces on the teeth are influenced by the strength and pattern of muscle contraction. Like dental lever arms, muscle tensions change with the bite point. Different muscles, each with a level of contraction specified by the central nervous system, are associated with tooth clenching at a particular site. Thus, the use of anterior bite points requires less contraction in fewer muscles than does biting on more posterior teeth [41, 42]. The physical need to maintain static equilibrium during clenching and the physiological constraints provided by periodontal sensory feedback (which regulates the bite force a given tooth can tolerate) together shape muscle contraction patterns.

The human periodontal ligament (PDL) stabilizes the tooth in bone and provides nutritive, proprioceptive, and reparative functions [43]. It is composed of collagenous fibers and a gelatinous ground substance including cells and neurovascular tissue. Under excessive pressure, as part of the self-protective features of the dentition, the periodontal and/or pulpal receptors induce negative feedback on the activity of the jaw elevators [44]. Biomechanically, the ligament demonstrates nonlinear viscoelasticity [45, 46, 47 and 48]. The biomechanical properties of alveolar bone and the periodontal ligament significantly influence bite force and the stress-bearing capabilities of the jaw [49]. Since the modulus of elasticity of the periodontium (approximately 2 to 3 MPa) [50, 51] is much less than that of mandibular cortical bone (approximately 10 to 20 GPa) [52], the maximum compressibility of the periodontal ligament will reach its limit prior to that of the mandibular cortical bone. During clenching, the molar teeth can resist more compression than the anterior teeth, due to their larger periodontal areas. In addition, the molar region of the mandible experiences more compressive load than the anterior region, due to the proximity of the masseter and the medial pterygoid muscles. Furthermore, some changes in bite force ratio could occur due to the influence of muscle co-activation and changes in the direction of muscular force [44]. Direction of force resulting from a given occlusal load is also important. Forces transmitted in an axial direction are best withstood. Horizontal forces are not tolerated as well as vertical forces and can cause bending of the tooth, thus creating compressive and tensile stresses [53].

Under physiological conditions, teeth are aligned in the jaw forming an arch. Adjacent proximal

surfaces of the crowns are usually in contact with one another. During mastication, forces are exerted on the teeth from the antagonist and through the food bolus. These forces can be exerted in different directions and are transmitted to adjacent teeth and periodontal ligaments. This redistribution of forces provides an efficient mechanism for protecting the teeth and the periodontium against trauma. Furthermore, these forces result in physiological tooth movements following the different components of force. Teeth are not only intruded into the alveoli, but are also tipped mesially and moved against one another. This gliding movement between proximal contacting surfaces of enamel results in wear and the development of a proximal contact area. The size, location and shape of these proximal contact areas depend on the anatomical surface contours of the two adjacent proximal surfaces, and whether they are on the mesial or distal aspects of the teeth. The proximal contact also plays an important role in protecting the periodontium against damage due to food impaction. The morphology of the area between the marginal ridges on the occlusal aspect of adjacent contacting teeth functions similar to a transverse fissure of a molar [54], deflecting the food to the buccal and/or lingual aspects of the teeth during chewing. If the proximal contact is strong enough to resist separation during the chewing action, food impaction will not occur. This resistance against separation is defined as proximal contact strenght. The viscoelastic properties of the periodontal ligament allows minute interdental displacements to occur. Under function, the teeth move in different directions according to the force vectors. Vertical components result in an intrusion into the alveolus, whereas horizontal forces result in primarily mesial dislocation. The mesial component is transmitted through the proximal contact over several teeth, following an exponential decay function [55]. It was postulated that the force transmission might cross the midline and end on the contralateral side in the canine area. However, the forces acting on the teeth should not be discussed in isolation. The alveolar bone, especially that of the mandible, has been shown to deform under function [56, 57 and 58]. Clenching between posterior teeth on the working side seems to induce tooth movement on the balancing side [57]. It is concluded that proximal contact strenght changes due to chewing, what might be explained by the combined effect of tooth intrusion and mandibular deformation. Time of day changes seem to be different from the changes due to chewing and could be explained by a fatigue behavior of the periodontal ligament. The proximal contact strenght, therefore, is not a static factor but seems to be influenced by a variety of internal and external factors [59].

From a biomechanical point of view may be concluded that perfect geometry of the occlusal surfaces and dental arch jointly with well-balanced occlusion guarantee physiologically acceptable distribution and compensation of the mastication forces, thus ensure long-lasting functioning of the teeth. Distribution of occlusal force on a dental arch should be considered from a viewpoint of movement of teeth, distortion of the mandible and positional relationship between bone and muscle. It is concluded, that the correlations between occlusal stability and elevator muscle function are probably based on feedback mechanisms from periodontal pressoreceptors. The periodontal ligament behaves as the biological shock absorber. Despite relevant command of muscles in the chewing apparatus, occlusion of the upper/lower jaws is constrained by joints and opposing teeth.

The human masticatory system is a mechanical system par excellence. Dentists know that all too well. They are constantly engaged in repairing the results of or consolidating the possibilities for mechanical functions like the breaking and crunching of food.This ideal from a functional viewpoint system may be damaged due to periodontal disease or partial dental loss. Present periodontitis shows changes of the clinical relation of the corona and radix of the tooth; increscent mobility of the teeth; changing position of the teeth in the dental arches; loss of the proximal contacts of the teeth; destruction of integrity and functional stability of the dental arch. Loss of the periodontal tissues results in disorganized periodontal sensory feedback due to decreased number of proprioceptors of the periodontal ligaments. In result physiological mastication forces affect traumatizing and stimulate course of the pathological process. Restoration of the functional integrity of the dental arch is one of the most relevant problems in clinical dentistry because functional equilibrium in and between the dental arches guarantee balanced functional stimulation of the masticatory apparatus and contributes to its harmonious development and maintenance.

REFERENCES

1. Koolstra JH, van Eijden T.. Three-dimensional dynamical capabilities of the human masticatory muscles. *J Biomech* 1999; 32:145–52.
2. Andrews JG. Hay JG. Biomechanical considerations in the modeling of muscle function. *Acta Morphol Neerl Scand* 1983; 21:199–223.
3. Lewin A. Electrognatographics: Atlas of Diagnostic Procedures and Interpretation. Chicago: Quintessence Publishing Co; 1985.
4. Blanksma NG, van Eijden TM, van Ruijven LJ, Weijs WA. Electromyographic heterogeneity in the human temporalis and masseter muscles during dynamic tasks guided by visual feedback. *J Dental Res* 1997; 76: 542–51.
5. Van der Helm FCT, Veenbaas R. Modelling the mechanical effect of muscles with large attachment sites: application to the shoulder mechanism. *J Biomech* 1991; 24: 1151–63.
6. Koolstra J.H., van Eijden T.M.G.J. Influence of the dynamical properties of the human masticatory muscles on jaw closing movements. *Eur J Morphol* 1996; 34:11–18.
7. Koolstra JH. Number crunching with the human masticatory system. *J Dental Res* 2003; 82: 672-6.
8. Huddleston Slater JJ, Visscher CM, Lobbczoo F, Naeije M. The intra-articular distance within the TMJ during free and loaded closing movements. *J Dent Res* 1999; 78:1815-1820.
9. Ferrario V, Sforza C. Biomechanical model of the human mandible: a hypothesis involving stabilizing activity of the superior belly of lateral pterygoid muscle. *J Prosthet Dent* 1992; 68(5):829-35.
10. Blankevoort L, Huiskes R, de Lange A.The envelope of passive knee motion. *J Biomech* 1988; 21:705–20.
11. Wang X, Maurin M, Mazet F, et al. Three-dimensional modelling of the motion range of axial rotation of the upper arm. *J Biomech* 1998; 31: 899–908.
12. Gribble P.L., Ostry D.J. Independent coactivation of shoulder and elbow muscles. Exp Brain Res 1998; 123:355–60.
13. Lindbeck L, Karlsson D, Kihlberg S, et al. A method to determine joint moments and force distributions in the shoulders during ceiling work—a study on house painters. *Clin Biomech* 1997; 12:452–60.
14. Koolstra JH. Dynamics of the human masticatory system. *Crit Rev Oral Biol Med* 2002; 13:366-76.
15. Miller A.J. Craniomandibular Muscles: Their Role in Function and Form, CRC Press Inc, Boca Raton, FL; 1991.
16. Hannam AG, McMillan AS. Internal organization in the human jaw muscles. *Crit Rev Oral Biol Med* 1994; 5:55–89.
17. Weijs WA. Evolutionary approach of masticatory motor patterns in mammals. *Adv Comp Environ Physiol* 1994; 18:283–320.
18. Yemm R. The role of tissue elasticity in the control of mandibular resting posture. In: Anderson DJ, Matthews B, editors. Mastication John Wright, Bristol; 1976. p. 81.
19. Rugh JD, Drago CJ, Barghi N. Comparison of electromyographic and phonetic measurements of vertical rest position. *J Dent Res* 1979; 58:316.

20. Miller AJ. Craniomandibular Muscles: Their Role in Function and Form, CRC Press Inc, Boca Raton, FL; 1991.
21. Hannam AG, Sessle BJ. Temporomandibular neurosensory and neuromuscular physiology. In: Zarb GA, Carlsson GE, Sessle BJ, Mohl ND, editors, Temporomandibular Joint and Masticatory Muscle Disorders, Chap. 3. Copenhagen: Munksgaard; 1994. p. 67.
22. Goto TK, Langenbach GEJ, Korioth TWP, et al. Functional movements of putative jaw muscle insertions. *Anat Rec* 1995; 242: 278–88.
23. Blanksma NG, van Eijden TM. Electromyographic heterogeneity in the human temporalis and masseter muscles during static biting, open/close excursions, and chewing. *J Dent Res* 1995; 74:1318–27.
24. Hattori Y, Satoh C, Seki S, et al. Occlusal and TMJ loads in subjects with experimentally shortened dental arches. *J Dent Res* 2003; 82:532-9.
25. Braun S, Bantleon HP, Hnat WP, et al. A study of bite force, part 1; Relationship to various physical characteristics. *Angel Orthod* 1995; 65(5): 367-72.
26. Hagberg C. Assessment of bite force—a review. *J Craniomandib Disord* 1987; 1:162–9.
27. Waltimo A, Kononen M. A novel bite force recorder and maximal isometric bite forces values for healthy young adults. *Scand J Dent Res* 1993; 101:171–5.
28. Ehrlich J, Taicher S. Intercuspal contacts of the natural dentition in centric occlusion. J Prosthet Dent 1981; 45: 419.
29. Pameijer JH, Glickman I, Roeber FW. Intraoral occlusal telemetry. III. Tooth contacts in chewing, swallowing and bruxism. *J Periodontol* 1969; 40:253-8.
30. Atkinson HF, Shepherd RW. Masticatory movements and the resulting force. *Arch Oral Biol* 1967; 12:195-202.
31. Ahlgren J, Owall B. Muscular activity and chewing force: a polygraphic study of human mandibular movements. *Arch Oral* Biol 1970; 15: 271-80.
32. Gibbs CH. Electromyographic activity during the motionless period in chewing. *J Prosthet Dent* 1975; 34: 35-40.
33. Okeson JP. Management of temporomandibular disorders and occlusion. 3rd ed. St. Louis: Mosby, 1993. p. 109-126.
34. Riise C, Ericsson SG. A clinical study of the distribution of occlusal tooth contacts in intercuspal position at light and hard pressure in adults. *J Oral Rehabil* 1983; 10: 473-80.
35. Hagberg C, Agerberg G, Hagberg M. Regression analysis of electromyographic activity of masticatory muscles versus bite force. *Scand J Dent Res* 1985; 93: 396-402.
36. Helkimo E, Carlsson GE, Helkimo M. Bite force and state of dentition. *Acta Odontol Scand* 1977; 35: 297-303.
37. Mansour RM, Reynik RJ. In vivo occlusal forces and moments: I. Forces measured in terminal hinge position and associated moments. *J Dent Res* 1975; 54:114-20.
38. . Rugh JD, Solberg WK. The measurement of human oral forces. *Behav Res Meth Instru* 1972; 4:125-128.
39. Hylander WL. The human mandible: Lever or link? *Am J Phys Anthropol* 1975; 43: 227-42.
40. Picq PG, Plavcan JM, Hylander WL. Nonlever action of the mandible: The return of the hydra. *Am J Phys Anthropol* 1987; 74: 305-7.
41. MacDonald JW, Hannam AG. Relationship between occlusal contacts and jaw-closing muscle activity during tooth clenching: Part I. *J Prosthet Dent* 1984; 52: 718-28.
42. MacDonald JW, Hannam AG. Relationship between occlusal contacts and jaw-closing muscle activity during tooth clenching: Part II. *J Prosthet Dent* 1984; 52:862-7.
43. Berkovitz BKB. The structure of the periodontal ligament: an update. European *Eur J Orthod* 1990; 12:51–76.
44. Kikuchi M, Korioth TWP, Hannam AG. The association among occlusal contacts, clenching effort and bite force distribution in man. *J Dent Res* 1997; 76:1316-26.
45. Wills DJ, Picton DC, Davies WI. An investigation of the viscoelastic properties of the periodontium in monkeys. *J Periodontal Res* 1972; 7:42–51.
46. Christiansen RL, Burstone CJ. Centers of rotation within the periodontal space. *Am J Orthod Dentofacial Orthop* 1969; 55(4):353–69.
47. Daly CH, Nicholls JI. The response of the human periodontal ligament to torsional loading - I. Experimental methods. *J Biomech* 1974; 5:517–22.
48. Picton DCA, Wills DJ. Viscoelastic properties of the periodontal ligament and mucous membrane. *J Prosthet Dent* 1978; 40 (3):263–72.
49. Daegling DJ, Ravosa MJ, Johnson KR, Hylander WL. Influence of teeth, alveoli, and periodontal ligaments on torsional rigidity in human mandibles. *Am J Phys Anthropol* 1992; 89: 59-72.
50. Ralph WJ. Tensile behaviour of the periodontal ligament. *J Periodont Res* 1982; 17: 423-6.
51. Mandel U, Dalgaard P, Viidik A. A biomechanical study of the human periodontal ligament. *J Biomech* 1986; 19: 637-45.
52. Dechow PC, Nail GA, Schwartz-Dabney CL, Ashman RB. Elastic properties of human supraorbital and mandibular bone. *Am J Phys Anthropol* 1993; 90: 291-306.
53. Kraus BM, Jordan RE, Abrams L. The self-protective features of the dentition. Dental anatomy and occlusion. Baltimore: Williams & Wilkins; 1969.
54. Ash MM. Wheeler's dental anatomy, physiology and occlusion. 7th ed. Philadelphia: W.B. Saunders; 1993. p.102-307.
55. Southard TE, Behrents RG, Tolley EA. The anterior component of occlusal force: Part 1. Measurement and distribution. *Am J Orthod Dentofacial Orthop* 1989; 96: 493-500.
56. Omar R, Wise MD. Mandibular flexure associated with muscle force applied in the retruded axis position. *J Oral Rehabil* 1981; 8: 209-21.
57. Picton DCA. Distortion of the jaws during biting. *Arch Oral Biol* 1962; 7: 573-80.
58. Korioth TWP, Hannam AG. Deformation of the human mandible during simulated tooth clenching. *J Dent Res* 1994; 73: 56-66.
59. Dorfer CA, von Bethlenfalvy ER, Staehle HJ, Pioch T. Factors influencing proximal dental contact strengths. *Eur J Oral S*ci 2000; 108:368-77.

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