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ORIGINAL ARTICLE

Neuromuscular control of balancing side contacts in unilateral biting and chewing

Daniela Schubert · Peter Pröschel · Christiane Schwarz · Manfred Wichmann · Thomas Morneburg

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Abstract When jaw gape in unilateral biting or chewing narrows, the working/balancing side activity ratio (W/B ratio) of masseter muscles increases due to decrease of balancing side (BS) activity. This was interpreted as a neuromuscular strategy to delimit the impact of BS contacts during chewing. To test this hypothesis, we studied whether W/B ratios are associated with incidence of BS tooth contacts. In 40 healthy subjects, bilateral masseter activity was recorded during unilateral biting with different jaw gapes and during various chewing tasks. Biting was performed with absence and with deliberate avoidance or generation of BS tooth contacts. Subjects were divided into three groups according to jaw gapes of 2, 1, and 0.5 mm for which BS contact was first noticed in strong biting. The smaller this gape was, the higher were the mean W/B ratios. In biting with contact avoidance, the W/B ratios in each group increased with decreasing gape. In biting with generation of BS contacts, W/B ratios were smaller than with contact avoidance. W/B ratios in chewing with minimum interocclusal distances below 0.5 mm were bigger than in biting with contact generation and were mostly bigger than in biting with contact avoidance. The findings confirm that increasing the masseter W/B ratio is a neuromuscular measure suitable to avoid BS contacts and support the idea that motor control uses jaw gape-related activation to limit the impact of BS contacts. Clarification of this protection mechanism might contribute to uncover the etiology of functional disorders and occlusal malfunctions.

D. Schubert · P. Pröschel (✉) · C. Schwarz · M. Wichmann · T. Morneburg
Dental Clinic 2, Department of Prosthodontics,
University of Erlangen-Nürnberg,
Glückstrasse 11,
91054 Erlangen, Germany
e-mail: peter.proeschel@uk-erlangen.de

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Introduction

It is still an unsettled question to what extent occlusal contacts are involved in the etiology of temporomandibular disorders and/or periodontal or occlusal damage. Research into this issue has led to differing statements because of widely varying experimental and functional conditions [1]. A major argument for the significance of tooth contacts was based on reports indicating that balancing side (BS) contacts can cause changes of jaw muscle activation [2–8]. Yet, despite such neuromuscular responses and widespread incidence in normal dentitions [9–13], BS contacts normally do not cause major problems [10, 14–18]. As such contacts are also common in mastication [7, 9, 12, 15, 18], it is likely that motor control uses a specific muscle activation strategy to master their impact. This supposed strategy is not easily obvious from the current knowledge of masticatory motor control. Mastication is driven by a central pattern generator (CPG) which alternately activates the jaw opener and closer muscles to generate the cyclic chewing movement [19, 20]. The chewing cycle is commonly divided into an opening phase followed by a fast-closing and a slow-closing phase [19]. During slow-closing, also referred to as “power stroke” or “occlusal phase,” the bite force increases to overcome the food resistance. Concurrently, the jaw closing movement slows down and stops when peak chewing force is reached [18, 19, 21, 22]. In this approximately isometric contraction [18, 23, 24], the jaw can tilt [15, 18, 25] about the compressed bolus which separates the teeth by some tenth of millimeters [26]. The tilting implies a slight elevation of the BS mandibular arch [27–31] which could result in direct BS tooth contacts [15, 25]. To prevent occlusal damage, the BS force had to be limited while high chewing force [32] is applied on the working side (WS). This kind of force control could in principle be enabled by afferent feedback from intramuscular and intraoral receptors [20, 33] which modifies the CPG output to the muscles. A known feedback mechanism is the facilitation of bite force by periodontal receptors [34, 35] which, however, does not explicate how control of different loads on both sides could be realized.

Recent studies suggest that an increase of the working/balancing side activity ratio (W/B ratio) of masseter muscles observed with decreasing jaw gapes in chewing and isometric biting might reflect the required kind of control [7, 26, 36]. An increase of the W/B ratio is equivalent to a reduction of the relative strength of the BS muscle. This could attenuate the slight lifting of the BS mandibular arch and could thus mitigate the effect of BS contacts. An increasing masseter W/B ratio was actually found during the approach of the mandible to the intercuspal position in masticatory power strokes of humans [37] and animals [38]. Likewise, the W/B ratio proved to increase with decreasing minimum interocclusal distances (MID) reached in sequent chewing strokes [26]. Finally, a like behavior of the W/B ratio was observed in unilateral isometric biting on silicone rubbers with graded decrease of thickness [36]. While this "jaw gape-related" control of masseter W/B ratios is well documented, its relation to BS tooth contacts is not yet established.

The aim of this study therefore was to test the hypothesis that jaw gape-related control of masseter W/B ratios is associated with the incidence of BS contacts in terms of an occlusal protection effect. Towards this purpose, we investigated W/B ratios in unilateral chewing and biting with and without BS contacts.

Materials and methods

Test subjects and experimental protocol

Twenty male and 20 female dental students (mean age, 23.6± 3.2 years) volunteered for this study. The subjects had complete angle class I or II dentitions and were free of signs or symptoms of temporomandibular disorders. Exclusion criteria were deep bite and skeletal anomalies like long or short face and malocclusions like mandibular prognathism. All subjects gave informed consent to the experimental protocol which was approved by the ethics committee of the medical faculty at Erlangen University. Each subject underwent one recording session during which he/she executed one right- and one left-sided trial of the following chewing and isometric biting tasks:

Task 1: unilateral chewing of industrially standardized samples of winegum (Goldbären, Haribo, Bonn, Germany),
Task 2: unilateral chewing of the same wingum as in task 1; however, these samples had been hardened by drying on open air for about 3 months. The subjects should chew with the same force as in task 1,
Task 3: unilateral chewing of chewing gum (Hubba Bubba Bubble tape, Wrigley GmbH, Unterhaching, Germany),
Task 4: unilateral chewing of the same kind of gum as in task 3, however, with the advice to apply an extra strong chewing force,
Tasks 5–8: unilateral intermittent isometric biting on pads of silicone rubber with 20 mm in length, 15 mm in width, and heights of 5, 2, 1, and 0.5 mm.

The different chewing tasks 1 to 4 were carried out to obtain functional data for conditions with expectedly differing MIDs and chewing forces. Apart from the stated prescriptions concerning chewing side (tasks 1–4) and force (tasks 2 and 4), chewing in all trials was done with the subjects' habitual rhythm and force. The biting trials of tasks 5–8 consisted of consecutive contractions and relaxations performed with a chewing-like rhythm and duration. Prior to the recording, the subjects positioned the rubber longitudinally between the lateral teeth in their accustomed chewing area and held it loosely between the teeth with the jaw in a non-eccentric posture. To ensure isometric contractions, the subjects were instructed to hold the rubbers loosely during the relaxation periods maintaining steady occlusal contact with the rubbers. The latter were administered in descending order of the thickness. With each thickness, the subjects first tested whether they experienced BS tooth contacts while they increased bite force up to maximum (Fig. 1). If they felt no BS contacts with a particular rubber thickness, they performed the actual trial with vigorous but submaximal bite forces according to their own psychophysical assessment. However, if they experienced BS contact in the test, this biting mode was replaced by two other trials with modified bite force applications: in the first trial, the subjects had to apply a force as high as possible and, however, submit to the condition that no BS contact occurred. Thereupon, in a second trial, they should bite so that they felt BS tooth contact without further advice concerning the height of the bite force. All subsequent trials with smaller thicknesses were then performed in the same way. Thus, a minimum of 16 trials were carried out per subject. This number could theoretically increase up to 24, depending on the thickness at which the biting tasks had to be split.

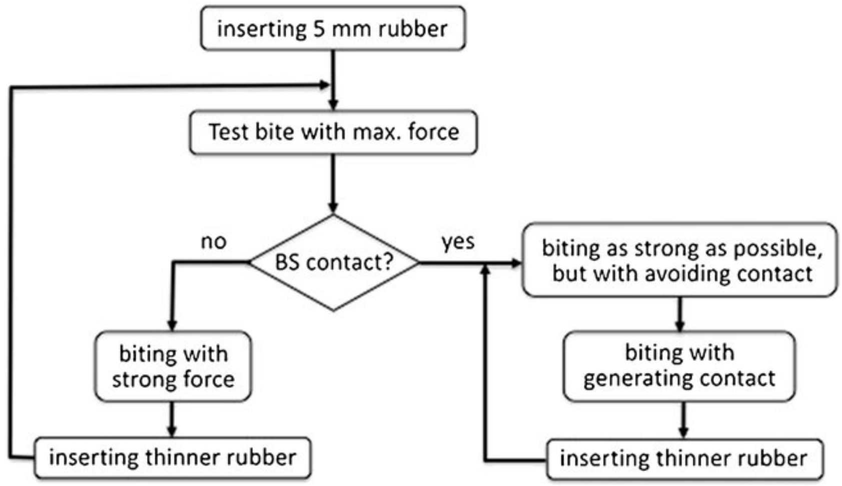

Fig. 1 Flow chart of the experimental protocol

Registration of surface EMGs and MIDs

For the recordings, the subjects were seated upright and comfortably in a wooden chair. The electric activities of right and left masseter muscles were recorded by means of active, disposable, self-adhesive bipolar Ag/AgCl surface electrodes with 10 mm polar diameter and 20 mm polar distance (Type 272, Noraxon, Scottsdale, AZ, USA). The electrode locations were determined by palpating the muscle bellies during chewing. Prior to attachment of the electrodes, the skin was cleaned with alcohol to reduce impedance. The electrodes were attached along the muscle fiber directions, and a reference electrode was fixed at the forehead. The raw EMGs were amplified by differential EMG amplifiers (Biovision, Wehrheim, Deutschland) wired close to the electrodes. The amplifiers had an input impedance of 10 GΩ, a common mode rejection ratio bigger than 120 dB, a noise level of 0.4 μV, and a bandwidth of 10 to 500 Hz with 3 dB. To determine MIDs, the chewing movements were recorded using a Sirognathograph (Siemens, Bensheim, Germany). This device traced the three-dimensional motion of a magnet fixed at the lower central incisors by means of self-curing resin (Pro Temp II, Espe Co. Seefeld, Germany). The spatial resolution of the Sirognathograph is 0.1 mm [39], and its linearity error is less than 1% within a cuboid of 15×15×25 mm edge length [40]. Standard precautions as reported previously [26] were taken in order to minimize disturbances of the movement signal. Before starting the recording, the bolus was placed on the tongue, the teeth were closed to maximum intercuspation, and the Sirognathograph signals were set to zero.

The jaw movement signals and the raw EMGs of each biting or chewing trial were sampled for 30 s at a rate of 2 kHz per channel by an 12-Bit A/D-converter (DAQ 6024, National Instruments, Austin, TX, USA) connected to a laptop (Inspiron 8600, Dell, Austin, TX, USA). Data sampling was controlled by a self-made software based on the DasyLab® graphic programming system version 8.0 (National Instruments, Austin, TX, USA).

Evaluation of data and statistics

The recordings were evaluated using a self-made routine also based on DasyLab®. The raw EMGs of each subject, trial, and muscle were automatically rectified and smoothed by a gliding average over 100 points corresponding to 50 ms. The time plots of movement and the smoothed EMG signals of each recording were displayed on the laptop. MIDs and activity peaks were determined as previously described [26], by manually moving a cursor-delimited window along the time plots. The MID was determined as the closest vertical distance to the baseline reached in each chewing cycle. Transversal and sagittal movement components were not evaluated. From the activity peaks of each chewing or biting cycle, the W/B ratios were calculated. Activities and activity ratios were averaged over the number of cycles obtained during each chewing or biting trial. Likewise, the MIDs were averaged over all cycles achieved in each chewing trial.

The biting trials were divided into groups according to the rubber thickness at which BS contacts first appeared. The EMG parameters and the MIDs were averaged over the number of cases within each of these groups. Differences between groups' mean values of activity ratios at the different jaw gapes were tested using a one-factorial analysis of variance. Differences between particular jaw gapes within the groups were tested by post-hoc Student's *t* tests for paired data. Differences between the groups at particular jaw gapes were tested by *t* tests for unpaired data.

Multiple testing was accounted for by a Bonferroni adjustment with a total significance level of $p=0.05$.

Results

Incidence of BS tooth contacts with the different jaw gapes

Occurrence of BS contacts in strong biting was first noticed at a rubber thickness

– of 5 mm by none of the participants,
– of 2 mm by five persons in right- and left-sided biting,
– of 1 mm by 11 persons in right- and by 16 persons in left-sided biting,
– of 0.5 mm by 16 persons in right- and by 17 persons in left-sided biting.

There were also three persons who did not experience any contact on either side, not even with the thinnest rubber. These cases were excluded from evaluation as they could not deliberately generate or avoid contacts. Right- and left-sided trials were pooled and divided into the following three groups according to the rubber thickness at which contacts first occurred:

Group G2: 10 trials with BS contact first noticed at a rubber thickness of 2 mm,
Group G1: 27 trials with BS contact first noticed at a rubber thickness of 1 mm,
Group G05: 33 trials with BS contact first noticed at a rubber thickness of 0.5 mm.

W/B ratios in biting with absence or avoidance of BS contacts

In all three groups, the W/B ratios at a thickness of 5 mm were about equally low with values between 1.1 to 1.3 (Fig. 2).

In G2, in biting with deliberate avoidance of BS contacts, the W/B ratio increased just slightly and insignificantly when the thickness was reduced from 5 to 0.5 mm. In G1, the W/B ratio increased significantly when the thickness was reduced to 2 mm in biting with no contacts. Then, in biting with deliberate avoidance of contacts, the ratio further increased significantly at 1 mm but decreased insignificantly at 0.5 mm thickness. The highest W/B ratios in biting with no contacts and the strongest significant increase of these ratios with decreasing thicknesses down to 1 mm were displayed by G05. In this group, the W/B ratio increased slightly and insignificantly with deliberate avoidance of contacts at 0.5 mm. For thicknesses of 2 mm and smaller, the W/B ratios with no contacts or contact avoidance in G1 as well as in G05 were significantly bigger than corresponding values in G2.

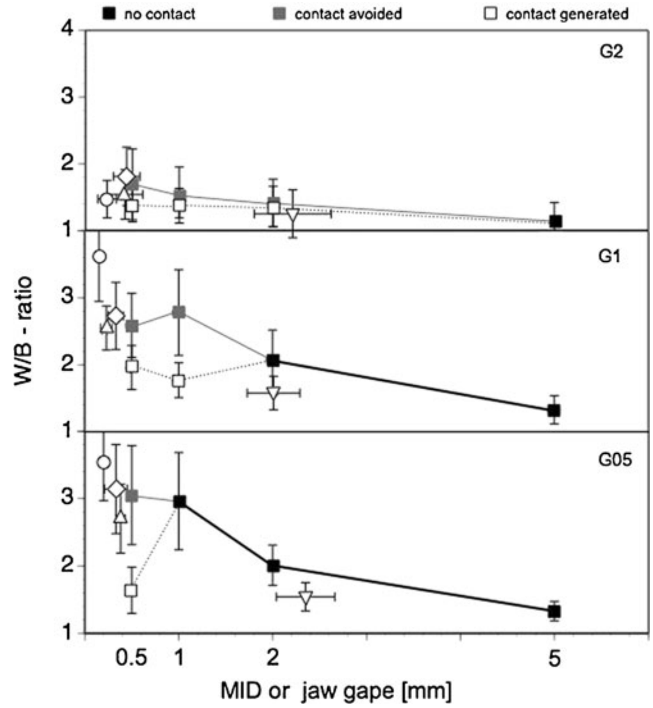

Fig. 2 Mean masseter W/B ratios in the three groups at the different jaw gapes in biting with absence of BS contacts (*black square*), with deliberate avoidance of BS contacts (*gray square*) and with deliberate generation of BS contacts (*white square*). For reasons of clarity, biting trials are connected by *lines*. In addition, mean W/B ratios for chewing of winegum (*white triangle*), hardened wine gum (*inverted white triangle*), gum chewing (*white diamond*), and gum chewing with strong force (*white circle*) are displayed. The *error bars* indicate the 95% confidence intervals

W/B ratios in biting with deliberate generation of BS contacts

In G2, BS contacts could be generated with 2, 1, and 0.5 mm rubber thickness (Fig. 2). Thereby, the W/B ratios were insignificantly smaller than with avoidance of contacts and did not change with decreasing thickness. In group G1, contacts could be produced with 1 and 0.5 mm. The corresponding W/B ratios were significantly smaller than when contacts were avoided. The same was observed for G05. In this group, the W/B ratio with contacts at 0.5 mm was also significantly smaller than when contacts were avoided at the same thickness.

W/B ratios and MIDs in chewing

In G2, the W/B ratios in mastication of winegum, chewing gum, and chewing gum with strong force did not differ significantly from the ratios of biting with or without contacts (Fig.2). Except of strong gum chewing in G1, the W/B ratios of these three chewing tasks in G1 and G05 did not differ significantly from the ratios of biting with contact avoidance at 0.5 mm. However, the W/B ratios of the three chewing tasks all were significantly bigger than the ratios of biting with deliberate generation of BS contacts at 0.5 mm gape. The mean MIDs of the three chewing tasks ranged between about 0.2 mm (chewing gum with strong force) and 0.4 mm (wine gum and chewing gum). In chewing of the hardened wine gum, the mean MIDs in the three groups ranged between 2 and 2.4 mm and the mean W/B ratios varied between 1.2 and 1.5.

Muscle activities with absence or avoidance of contacts

In all groups, the activities decreased for jaw gapes at which contact was possible but was avoided: Group G2 displayed a high WS activity at 5 mm gape, where no contact occurred (Fig. 3). With decreasing gape, the activity decreased significantly when contact was avoided. With group G1, the WS activities were about equal at gapes of 5 and 2 mm (no contact possible) and then decreased significantly when contact was avoided at 1 and 0.5 mm. Group G05 displayed an analogous behavior, with fairly constant high WS activities at gapes of 5, 2, and 1 mm (no contact possible) and with a significant decrease at 0.5 mm. The BS activities performed similar to the WS activities but were generally lower than the latter.

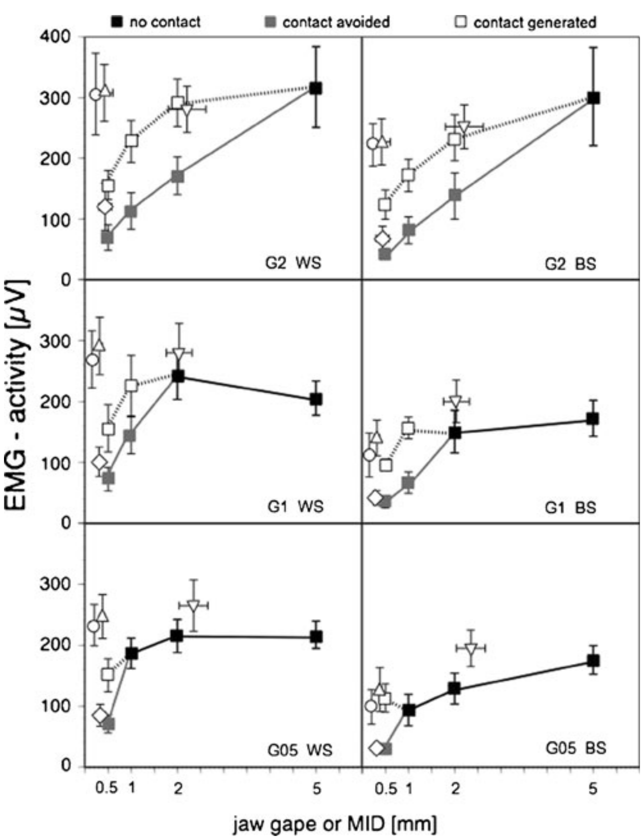

Fig. 3 Mean masseter muscle activities in the three groups at the different jaw gapes in biting with absence of BS contacts (*black square*), with deliberate avoidance of BS contacts (*gray square*) and with deliberate generation of BS contacts (*white square*). For reasons of clarity, biting trials are connected by *lines*. In addition, mean muscle activities for chewing of winegum (*white triangle*), hardened wine gum (*inverted white triangle*), gum chewing (*white diamond*), and gum chewing with strong force (*white circle*) are displayed. The *error bars* indicate the 95% confidence intervals

Muscle activities in biting with deliberate generation of BS contacts

With decreasing gapes, the activities in biting with contacts decreased significantly on both sides (Fig. 3). However, the activities all were significantly higher than when contacts had been avoided with the corresponding jaw gapes.

Muscle activities in chewing

In chewing of wingum, hardened winegum, and in strong gum chewing, the muscle activities in all three groups and on each side in most cases were significantly higher than muscle activities obtained in the biting tasks at comparable jaw gapes of 0.5 or 2 mm (Fig. 3). In contrast, the muscle activities with gum chewing were significantly smaller than those of the other chewing tasks and were rather close to the activities of biting with avoidance of contacts.

Discussion

The study hypothesis that masseter W/B ratios in unilateral biting and chewing are associated with BS tooth contacts in terms of occlusal protection is widely supported by the findings. At first, the results indicate an association between the W/B ratio and the jaw gape at which tooth contact first occurred. The smaller this gape was, the higher were the W/B ratios. Based on biomechanical reasoning, this could be viewed as a protective effect: With unilateral loading, BS lever arms of muscles are several times longer than WS lever arms [41]. Hence, if masseters on both sides act equally, as usually observed with bigger jaw gapes [36], the jaw tilts about the bitten object and lifts on the BS [27–31]. If the height of the WS fulcrum drops below an individual limit, the BS teeth apparently can come into contact. A possibility to counteract this contacting without strongly affecting the bite force is by reducing the strength of the BS masseter relative to that of the WS muscle [41]. This implies an increase of the W/B ratio and hence an increase of side-related asymmetry of muscle activities. The more asymmetrically the masseters act with a given biting strength, the less should the BS mandibular arch be lifted and the smaller should the gape be at which contact is first noticed. This is well reflected by the results: With most symmetrical activations (G2), BS teeth contacted already at a gape of 2 mm, indicating the biggest BS lifting. With more asymmetrical activations (G1 and G05), BS teeth contacted not until gapes of 1 or 0.5 mm, respectively, were reached. The smaller the jaw gape is, at which contacts occur, the less likely will be their incidence in chewing of varying food textures. Therefore, the increase of W/B ratios in biting with decreasing gapes without contacts represents a motor control feature which clearly favors prevention of contacts. This partially applies as well to biting with contact avoidance in G1 or G05 (Fig. 2), In this case, W/B ratios increased more (G1) or less (G2, G05) strongly with decreasing gape (grey squares in Fig. 2), yet muscle activities dropped strongly and almost linearly (grey squares in Fig. 3). It thus appears that with decreasing jaw gape, BS contacts are at first prevented by an engrammed increase of the masseter W/B ratio while activity levels are maintained (G1 at 5 and 2 mm and G05 at 5, 2, and 1 mm). When gapes then drop below a certain limit, the deliberate attempt to bite strongly but to avoid contacts is not achieved by increasing W/B ratios alone but is assisted by reducing all muscle activities.

In biting with deliberately generated BS contacts, W/B ratios were smaller than with contact avoidance (Fig. 2) but were still significantly bigger than 1.0 (G1 and G2). This suggests that BS teeth were loaded less strongly than WS teeth. With decreasing gapes, additional limitation of BS tooth loads was indicated by the strong reductions of muscle activities (Fig. 3). As no advice concerning the biting strength had been given in this task, these activity reductions may have been reflectively triggered by the direct contacts.

Though BS contacts could not be verified directly in mastication, they quite certainly emerged in chewing of winegum and in both gum chewing tasks. This is likely since MIDs ranged below 0.5 mm for which in the biting trials contacts had occurred in all subjects. To avoid overloading of these contacts, a strong reduction of force like in biting with contact avoidance seems counterproductive. In view of the study hypothesis, rather an increase of W/B ratios should be expected. The W/B ratios in the abovementioned chewing tasks match this expectation (Fig. 2) as they were equal to or bigger than corresponding values of biting with contact avoidance.

Occlusal protection by jaw gape-related control of W/B ratios needs to be aligned with customary views of protection by reflectory muscle inhibition (for an extensive review, see [33]). Such views are mainly based on unloading reflexes studied in clenching or simulated chewing experiments. These were mostly performed with big jaw gapes [33, 42–48] and with inhibitory responses elicited by extra- or intraoral stimuli but not by direct tooth contacts. Several arguments question the suitability of reflex control for occlusal protection in masticatory power strokes: Due to latencies, inhibition of muscle force possibly triggered by tooth contacts would be delayed and would counteract the buildup of chewing force [18, 33]. Further, inhibitory reflexes lose effectiveness when jaw gapes decrease [42–45]. Hence, it was supposed that close to occlusion, inhibitory response to unharmful stimuli is reduced so that the required rise of chewing force is not disrupted [33, 43, 46, 49]. This could explain why in real mastication silent periods of muscle activity occurring together with tooth contacts did not entail force inhibitions [18, 49, 50].

Jaw gape-related control can compensate the potential shortcomings of reflex control. Firstly, the reduction of BS masseter activity is a protective effect acting selectively on the BS. Secondly, the decrease of BS activity starts in advance to BS contacts as evident from the increase of W/B ratios in G1 and G05 in biting with absence of contacts (Fig. 2). Hence, in contrast to reflex control, the increase of the W/B ratio is an engrammed behavior with a preventive character. The actual effect of this behavior may be to accomplish a cautious approach of BS teeth which may end up in mitigated contacts that do not elicit reflectory inhibition. Once contact is made, a "load- or touch-related" response by BS periodontal receptors [51] might contribute to a steady limitation of contact loading. The high W/B ratios found with the smallest MIDs in strong gum chewing (Fig. 2) could indicate such a mechanism.

Jaw gape-related control operates close to occlusion but does not compete with reflectory control at bigger jaw separations. For example, in breaking of brittle food, sequent unloading reflexes triggered by cracking sounds or vibrations cause force inhibitions that help to keep the jaws from clashing [18, 33, 49, 50, 52]. These cracking events happen at jaw separations of some millimeters where gape-related control is less effective [26, 36]. This is corroborated by the small W/B ratios with MIDs around 2 mm as displayed in chewing of the hardened winegum (Fig. 2).

The present findings and interpretations should be considered as circumstantial evidence which should encourage further research. For example, it is unclear why jaw gape-related activation was so weakly developed in G2 compared to G1 and G05. One reason might be that temporalis partitions influence loading of the temporomandibular joints [53–56] which could have affected masseter muscle balance. Though it is likely that jaw gape-related activation is controlled by muscle spindle output, it would be indicated to clarify the influence of other possible afferent sources. As jaw gape-related activation would ensure a physiological masticatory function, it would further be interesting to clarify whether and how this strategy transforms in case of malfunctions and disorders.

Conclusions

Subject to experimental limitations, the results suggest that an increasing W/B ratio of masseter muscles favors the prevention of BS tooth contacts when the jaw gape decreases in strong biting. If the gape drops below an individual threshold, contacts can occur. Deliberate avoidance of such contacts is achieved by motor control by moderately increasing the W/B ratio and strongly reducing the muscle activities. In undeliberate chewing, W/B ratios become exceptionally high if contact incidence becomes likely at small MIDs. The findings, except those for G2, provide further evidence for the assumption that human motor control applies a strategy primarily based on proprioception of the interocclusal distance to limit the impact of BS tooth contacts in unilateral biting or chewing.

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Conflict of interest The authors declare that they have no conflict of interest.

References

1. Clark GT, Tsukiyama Y, Baba K, Watanabe T (1999) Sixty-eight years of experimental occlusal interference studies: what have we learned? J Prosthet Dent 82:704–713
2. Ramfjord SP (1961) Temporomandibular joint dysfunction. J Prosthet Dent 11:353–374
3. Belser UC, Hannam AG (1985) The influence of altered working-side occlusal guidance on masticatory muscles and related jaw movement. J Prosthet Dent 53:406–413
4. MacDonald JW, Hannam AG (1984) Relationship between occlusal contacts and jaw-closing muscle activity during tooth clenching: part I. J Prosthet Dent 52:718–729
5. MacDonald JW, Hannam AG (1984) Relationship between occlusal contacts and jaw-closing muscle activity during tooth clenching: part II. J Prosthet Dent 52:862–867
6. Van Eijden TMGJ, Blanksma NG, Brugman P (1993) Amplitude and timing of EMG activity in the human masseter muscle during selected motor tasks. J Dent Res 72:599–606
7. Nishigawa K, Nakano M, Bando E (1997) Study of jaw movement and masticatory muscle activity during unilateral chewing with and without balancing side molar contacts. J Oral Rehabil 24:691–696
8. Mizutani H, Shinogaya T, Xoneda K, Iso K, Ai M (1989) Influence of tooth contacts on masseter and temporal muscle activity. 1. Total activity and its ratio to maximum biting activity in intercuspal position (IP ratio). Nihon Hotetsu Shika Gakkai Zasshi 33:1062–1071
9. Anderson DJ, Picton DCA (1957) Tooth contact during chewing. J Dent Res 36:21–26
10. Ingervall B, Carlsson GE (1982) Masticatory muscle activity before and after elimination of balancing side occlusal interference. J Oral Rehabil 9:183–192
11. Woda A, Vigneron P, Kay D (1979) Nonfunctional and functional occlusal contacts: a review of the literature. J Prosthet Dent 42:335–341
12. Mohamed SE, Harrison JD, Christensen LV (1996) Masticatory tooth contact patterns: cuspid and first molar contacts during mastication of three types of food. J Craniomandib Pract 14:266–273
13. Ogawa T, Koyano K, Tsukiyama M, Tsukiyama Y, Sumiyoshi K, Suetsugu T (1998) Difference in the mechanism of balancing-side disclusion between 1st an 2nd molars. J Oral Rehabil 25:430–435
14. DeBoever JA, Carlsson GE, Klineberg IJ (2000) Need for occlusal therapy and prosthodontic treatment in the management of temporomandibular disorders. Part I. Occlusal interferences and occlusal adjustment. J Oral Rehabil 27:367–379
15. Mohamed SE, Christensen LV, Harrison JD (1983) Tooth contact patterns and contractile activity of the elevator jaw muscles during mastication of two different types of food. J Oral Rehabil 10:87–95
16. Agerberg G, Sandström R (1988) Frequency of occlusal interferences: a clinical study in teenagers and young adults. J Prosthet Dent 59:212–217
17. Seligman DA, Pullinger AG (1991) The role of functional occlusal relationships in temporomandibular disorders: a review. J Craniomandib Disord 5:265–279
18. Anderson DJ (1976) The incidence of tooth contacts in normal mastication and the part they play in guiding the final stage of mandibular closure. In: Anderson DJ, Mathews B (eds) Mastication. John Wright, Bristol
19. Lund JP (1991) Mastication and its control by the brain stem. Crit Rev Oral Biol Med 1:33–64
20. Lund JP, Kolta A (2006) Generation of the central masticatory pattern and its modification by sensory feedback. Dysphagia 21:167–174
21. Anderson K, Throckmorton GS, Buschang PH, Hayasaki H (2002) The effects of bolus hardness on masticatory kinematics. J Oral Rehabil 29:689–696
22. Morneburg TR, Proeschel PA (2003) In vivo forces on implants influenced by occlusal scheme and food consistency. Int J Prosthodont 16:481–486
23. Weijs WA (1980) Biomechanical models and the analysis of form: a study of the mammalian masticatory apparatus. Am Zool 20:707–719
24. Slagter AP, Bosman F, Van der Glas HW, Van der Bilt A (1993) Human jaw- elevator muscle activity and food comminution in the dentate and edentulous state. Arch Oral Biol 38:195–205
25. Möller E (1966) The chewing apparatus. Acta Physiol Scand 69 (Suppl 280):1–229
26. Pröschel PA, Morneburg TR (2010) Indications for jaw gape-related control of relative muscle activation in sequent chewing strokes. J Oral Rehabil 37:178–184
27. Korioth TW, Hannam AG (1994) Deformation of the human mandible during simulated tooth clenching. J Dent Res 73:56–66
28. Baba K, Yugami K, Yaka T, Ai M (2001) Impact of balancing-side tooth contact on clenching induced mandibular displacements in humans. J Oral Rehabil 28:721–727
29. Okano N, Baba K, Ohyama T (2005) The influence of altered occlusal guidance on condylar displacement during submaximal clenching. J Oral Rehabil 32:714–719
30. Palla S, Gallo LM, Gossi D (2003) Dynamic stereometry of the temporomandibular joint. Orthod Craniofac Res 6(Suppl 1):37–47
31. Kuboki T, Azuma Y, Orsini MG, Takenami Y, Yamashita A (1996) Effects of sustained unilateral molar clenching on the temporomandibular joint space. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 82:616–624

32. Pröschel PA, Morneburg TR (2002) Task-dependence of activity/bite-force relations and its impact on estimation of chewing force from EMG. J Dent Res 81:464–468
33. Türker KS (2002) Reflex control of human jaw muscles. Crit Rev Oral Biol Med 13:85–104
34. Lavigne G, Kim JS, Valiquette C, Lund JP (1987) Evidence that periodontal pressoreceptors provide positive feedback to jaw closing muscles during mastication. J Neurophysiol 58:342–358
35. Morimoto T, Inoue T, Masuda Y, Nagashima T (1989) Sensory components facilitating jaw-closing muscle activities in the rabbit. Exp Brain Res 76:424–440
36. Pröschel PA, Jamal T, Morneburg TR (2008) Motor control of jaw muscles in chewing and in isometric biting with graded narrowing of jaw gape. J Oral Rehabil 35:722–728
37. Kimoto K, Fushima K, Tamaki K, Toyoda M, Sato S, Uchimura N (2000) Asymmetry of masticatory muscle activity during the closing phase of mastication. J Craniomandib Pract 18:257–263
38. Jüch PJW, Minkels RF, van Willigen JD (1993) Inhibitory commissural connections of neurones in the trigeminal motor nucleus of the rat. Arch Oral Biol 38:1083–1091
39. Throckmorton GS, Ellis E 3rd, Hayasaki H (2003) Jaw kinematics during mastication after unilateral fractures of the mandibular condylar process. Am J Orthod Dentofacial Orthop 124:695–707
40. Mongini F, Tempia-Valenta G (1984) A graphic and statistical analysis of the chewing movements in fubction and dysfunction. J Craniomandib Pract 2:125–134
41. Ito T, Gibbs CH, Marguelles-Bonnet R, Lupkiewicz SM, Young HM, Lundeen HC, Mahan PE (1986) Loading of the temporomandibular joints with five occlusal conditions. J Prosthet Dent 56:478–484
42. Van der Bilt A, Ottenhoff FAM, van der Glas HM, Bosman F, Abbink JH (1997) Modulation of the mandibular stretch reflex sensitivity during various phases of rhythmic open-close movements in humans. J Dent Res 76:839–847
43. Lobbezoo F, Sowman PF, Türker KS (2009) Modulation of human exteroceptive jaw reflexes during simulated mastication. Clin Neurophysiol 120:398–406
44. Mostafeezur RM, Yamamura K, Kurose M, Yamada Y (2009) Mastication- induced modulation of the jaw-opening reflex during different periods of mastication in awake rabbits. Brain Res 1254:28–37
45. Naser-ud-Din S, Sowman PF, Dang H, Türker KS (2010) Modulation of masseteric reflexes by simulated mastication. J Dent Res 89:61–65
46. Appenteng K, Lund JP, Seguin JJ (1982) Intraoral mechanoreceptor activity during jaw movement in the anaesthetized rabbit. J Neurophysiol 48:27–37
47. Cadden SW, Newton JP (1988) A comparison of reflex depressions of activity in jaw-closing muscles evoked by intra and perioral stimuli in man. Arch Oral Biol 33:863–869
48. Hück NL, Abbink JH, Hoogenkamp E, van der Bilt A, van der Glas HW (2005) Exteroceptive reflexes in jaw-closing muscle EMG during rhythmic jaw closing and clencing. Exp Brain Res 162:230–238
49. Stohler CS, Ash MM (1984) Silent period in jaw elevator muscle activity during mastication. J Prosthet Dent 52:729–735
50. Owall B, Elmqvist D (1975) Motor pauses in EMG activity during chewing and biting. Odontol Revy 26:17–38
51. Trulsson M, Johansson RS (1996) Encoding of tooth loads by human periodontal afferents and their role in jaw motor control. Prog Neurobiol 49:267–284
52. Müller F, Heath MR, Kazazoglu E, Hector MP (1993) Contribution of periodontal receptors and food qualities to masseter muscle inhibition in man. J Oral Rehabil 20:281–290
53. Hatcher DC, Faulkner MG, Hay A (1986) Development of mechanical and mathematical models to study temporomandibular joint loading. J Prosthet Dent 55:377–384
54. Lobbezoo F, Zwijnenburg AJ, Naeije M (2000) Functional subdivision of the human masseter and temporalis muscles as shown by the condylar movement response to electrical muscle stimulation. J Oral Rehabil 27:887–892
55. Schindler HJ, Rues S, Türp JC, Schweizerhof K, Lenz J (2005) Activity patterns of the masticatory muscles during feedback-controlled simulated clenching activities. Eur J Oral Sci 113:469–478
56. Fushima K, Gallo LM, Krebs M, Palla S (2003) Analysis of the TMJ intraarticular space variation: a non-invasive insight during mastication. Med Eng Phys 25:181–190