



Influence of bite force on jaw muscle activity ratios in subject-controlled unilateral isometric biting

Lei Chen^a, Peter Alfred Pröschel^{b,*}, Thomas Riccardo Morneburg^b

^a Dept. of Prosthodontics, Peking University School and Hospital of Stomatology, 22 Zhongguancun Nandajie, Haidan District, Beijing 7000 87, PR China

^b Dental Clinic 2, Department of Prosthodontics, University of Erlangen-Nürnberg, Glückstrasse 11, D 91054 Erlangen, Germany

ARTICLE INFO

Article history:

Received 20 July 2009

Received in revised form 3 March 2010

Accepted 24 March 2010

Keywords:

Elevator muscles

Isometric biting

EMG

Bite force

Activity ratio

ABSTRACT

Ratios of muscle activities in unilateral isometric biting are assumed to provide information on strategies of muscle activation independently from bite force. If valid, this assumption would facilitate experiments as it would justify subject-control instead of transducer-based force control in biting studies. As force independence of ratios is controversial, we tested whether activity ratios are associated with bite force and whether this could affect findings based on subject-controlled force. In 52 subjects, bite force and bilateral masseter and temporalis electromyograms were recorded during unilateral biting on a transducer with varying force levels and with uniform subject-controlled force. Working/balancing and temporalis/masseter ratios of activity peaks were related to bite force peaks. Activity ratios were significantly but weakly correlated with the bite force. The subject-controlled force varied within $\pm 25\%$ around the prescribed force in 95% of all bites. This scatter could cause a variation of group mean activity ratios of at most $\pm 6\%$ because of the weak correlation between bite force and ratios. As this small variation is negligible in most cases, subject-control of bite force can be considered an appropriate method to obtain group means of relative muscle activation in particular when force control with transducers is not feasible.

© 2010 Elsevier Ltd. All rights reserved.

1. Introduction

Ratios of jaw muscle activities measured by surface electromyography (EMG) provide useful information on the biophysical principles of mandibular function. In particular for the case of unilateral isometric biting, activity ratios have been analyzed to elucidate neuromuscular objectives underlying specific craniomandibular load distributions and muscle activations (Barbenel, 1974; Faulkner et al., 1987; Throckmorton, 1989; Throckmorton et al., 1990; Erhardson et al., 1993; Ferrario and Sforza, 1994; Iwasaki et al., 2003; Pröschel et al., 2008). The ratios are thereby considered as surrogates for relative muscle strengths that balance craniomandibular reaction forces. Generalization of results obtained under such conditions requires that group means of activity ratios are not affected by a variation of bite force within certain limits. This precondition is not unchallenged since for example in mastication activity ratios were found to vary in response to food texture (Hylander et al., 1992; Blanksma and Van Eijden, 1995; Piacino et al., 2008).

In isometric biting there is little evidence to support the assumption of force independence of activity ratios (Mao and

Osborn, 1994). This assumption is rather based on empirical properties of EMG/bite force relations. Group means of activity ratios would be independent from the bite force if EMGs of the muscles involved were linearly related to the force and if the regression lines pass through the origins of the EMG/bite force diagrams. In this case, bite force would cancel and activity ratios would correspond to slope ratios of the EMG/bite force regressions of the muscles involved. While there is ample evidence for linearity in a submaximal force range (Pruim et al., 1978; Bakke et al., 1989; Van Eijden et al., 1990; Lindauer et al., 1991; Proeschel and Raum, 2001), some reports indicate that regression lines do not always intersect at the origin (Pruim et al., 1978; Bakke et al., 1989; Van Eijden et al., 1990; Lindauer et al., 1991). This might be due to various factors such as changing bite force directions (Van Eijden et al., 1990; Mao and Osborn, 1994; Rues et al., 2008) or heterogeneous activation of muscle compartments (Belser and Hannam, 1986; Blanksma and Van Eijden, 1995). Study or control of such factors requires standardized non-habitual motor tasks (Rues et al., 2008) and involves complex techniques that impede biting with direct occlusal contact or with small jaw gaps.

When habitual biting under conditions close to normal function is studied, the control of force level and/or direction is commonly left to the subjects' self-assessment. Even though the majority of published EMG-biting studies have been performed under such

* Corresponding author. Tel.: +49 9131 8534223; fax: +49 9131 8536781.
E-mail address: Peter.Proeschel@uk-erlangen.de (P.A. Pröschel).

non-standardized conditions, it is not yet established how strongly a subject-controlled bite force can vary and how this would influence the activity ratios. A causative stochastic influence of bite force on activity ratios could affect the significance and general validity of findings based on relative activations. Hence the objective of the present study was to clarify whether activity ratios are related to the bite force and if so, whether this correlation could affect the validity of results based on subject-controlled force in unilateral biting tasks.

2. Materials and methods

2.1. Subjects

Fifty-two male dental students (mean age 23.6 ± 3.2 yrs) participated in this study. The subjects had complete Angle Class I or II dentitions and no signs or symptoms of temporomandibular disorders, no skeletal anomalies like long or short face and no malocclusions like mandibular prognathism. All subjects gave informed consent to the experimental protocol which was approved by the Ethics Committee of the Faculty of Medicine at Erlangen University.

2.2. Experimental protocol

In one recording session, each subject carried out two different tasks of unilateral intermittent isometric biting on a force transducer which was placed between the teeth in the area of the second premolar and the first molar on the right side. Intermittent biting consisted of consecutive contraction–relaxation cycles performed with a chewing-like frequency. During each task, the surface electromyograms of elevator muscles on each side and the bite force were recorded for 20 s.

In the first task, the subjects were advised to bite with differing force levels in order to achieve EMG–bite force regressions. Grading of the forces within a submaximal range was facilitated by visual feedback of the bite force which was indicated as a horizontal line on an oscilloscope screen. Prior to the actual registration, 4–7 bites were carried out with maximum force during which the oscilloscope gain was adjusted such that the force indicator did not exceed the top of the screen. The screen was divided vertically into three sections with equal heights corresponding to a “low”, “medium” and “high” force range. For the actual registration, the subjects were advised to bite intermittently so that the force indicator arrived within each of the three force ranges in ascending order (Fig. 1). These triples of bites were repeated continuously throughout the 20 s recording time.

In the second task the subjects had to bite intermittently with a chewing-like rhythm but with uniform peak forces that should correspond to the same force as in chewing of gummibears. To meet this condition, the subjects chewed several gummibears (Haribo, Germany) prior to the registrations and then tried to bite with the same force on the transducer. During the second task no optical feedback was provided.

2.3. Registration of surface EMGs and bite force

The electric activities of the right (working side – WS) and left (balancing side – BS) masseter and anterior temporalis muscles were recorded using bipolar recessed Ag/AgCl – surface electrodes with 2 mm polar diameter and 20 mm center to center polar distance (Hellige, Freiburg, Germany). Prior to attachment, the electrode sites were determined by palpating the muscle bellies during chewing. To reduce impedance, the skin was cleaned with alcohol and mildly rubbed with abrasive paper. The electrodes

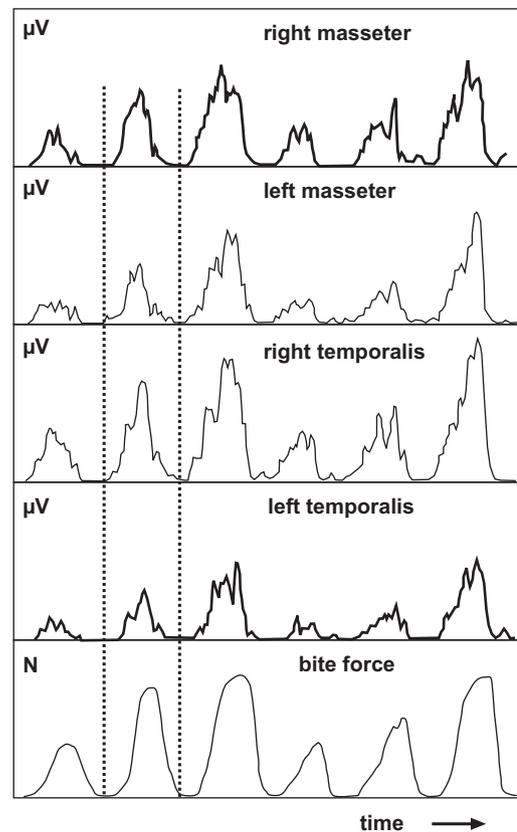


Fig. 1. Example showing six intermittent bites performed repeatedly with three different force levels, redrawn from a section of an original 20 s recording. The dotted vertical lines illustrate the two cursors that were placed in the semi-automatic evaluation on the computer monitor to enclose all EMG peaks and the bite force peak of each consecutive bite.

were filled with conductive paste and attached using adhesive film. The bipolar electrodes were aligned along the muscle fiber direction on each muscle. A reference electrode was attached to the right wrist of each subject. The raw EMGs were amplified, filtered (10 Hz to 2 kHz), full-wave rectified and smoothed electronically corresponding to root-mean-square (r.m.s.) averaging with a 40-ms time constant (Digital EMG system 1500[®], Disa, Denmark). The amplifiers had an input impedance of 250 M Ω , a common mode rejection ratio greater than 100 dB and a noise level of 0.4 μ V both between 2 Hz and 10 kHz. Bite force was measured by means of a metal bite fork equipped with a strain gage (Proeschel and Raum, 2001). The biting lips had areas of 10 \times 15 mm and were cushioned with 1 mm layers of silicone rubber causing a jaw gape of 6 mm. The strain gage was wired as one arm of a Wheatstone bridge. The bridge circuit was driven by a carrier frequency amplifier (TF19, Hellige, Freiburg, Germany). Prior to the recordings the bite fork was calibrated by means of an industrial load cell (U2B, Hottinger Baldwin Me \ddot{u} stechik, Darmstadt, Germany). The r.m.s. EMGs and the force signals were sampled by a 12-Bit A/D converter (Multiprogrammer 6944A, Hewlett Packard, Palo Alto, California, USA) at a rate of 100 Hz and stored on a hard disc.

2.4. Evaluation of data and statistics

The r.m.s. EMGs of the four muscles and the bite force signal of each 20 s recording were displayed on a computer (HP320, Hewlett Packard, Palo Alto, Ca, USA). In a semi-automated evaluation using dedicated in-house software, two cursors were moved manually by

means of a mouse along the time plots of the five channels. The cursors were placed so that they enclosed the four EMG peaks and the force peak of each bite (Fig. 1). The enclosed peak values were output by the program and stored in separate files for further analysis.

For the first task, the working/balancing (W/B) ratios of masseter and temporalis activities and the temporalis/masseter (T/M) ratios of working side (WS) and balancing side (BS) activities were calculated from the corresponding peaks. For each subject, the mean of all force peaks obtained during one recording was calculated and all force peaks of the recording were normalized to this mean which was set to 100%. Likewise for each subject, the W/B- and T/M-ratios and the activity peaks were normalized to the respective means of each recording. The normalized activity peaks and the normalized W/B- and T/M-ratios were related to the normalized bite force peaks using linear and second order polynomial regression. A regression was considered significant for $p < 0.01$. To clarify whether axis intercepts of activity/bite-force regressions differed from zero, a *U*-test was performed on the residuals of the linear and non-linear regressions. For this purpose, the residuals were shifted along the regression lines to $x = 0$ so that their mean was equal to the *y*-axis intercept and it was tested whether this mean differed from zero. All statistical procedures were performed with the Statview software for Macintosh (Abacus Concepts, Berkeley, CA, USA).

From the second biting task in which subjects applied a self-determined chewing-like force, the mean value and the scatter of the force peaks achieved by each subject over the duration of the

task were determined. The deviations of the force peaks from the mean were standardized as percentages of the individual mean.

3. Results

3.1. Relations between activities and bite force

During the 20 s recording time the subjects on average performed 23 ± 3 contractions. Biting with the three force levels yielded a mean “low” force of 155 ± 66 N, a “medium” force of 324 ± 78 N and a “high” force of 469 ± 108 N.

The activity of each muscle was correlated significantly ($p < 0.0001$) with the bite force (Fig. 2). As indicated by the *r*-values, the polynomial activity/bite force (A/FB) regressions were marginally stronger than the linear regressions. All axis intercepts of both regression modes intersected the activity axes at positive values ($p < 0.001$). In particular, the *y*-intercepts of the BS masseter and the WS temporalis A/FB regression curves deviated markedly from the origin (Fig. 2).

3.2. Relations between activity ratios and bite force

The W/B- and T/M-ratios of the grouped subject data were weakly but significantly ($p < 0.001$) correlated with the bite force (Fig. 3, Table 1). As indicated by the curves and the *r*-values, the polynomial regressions nearly matched the linear regressions but were marginally stronger. The W/B-ratio of the masseter and the T/M-ratio on the BS slightly increased with force, the W/B-ratio

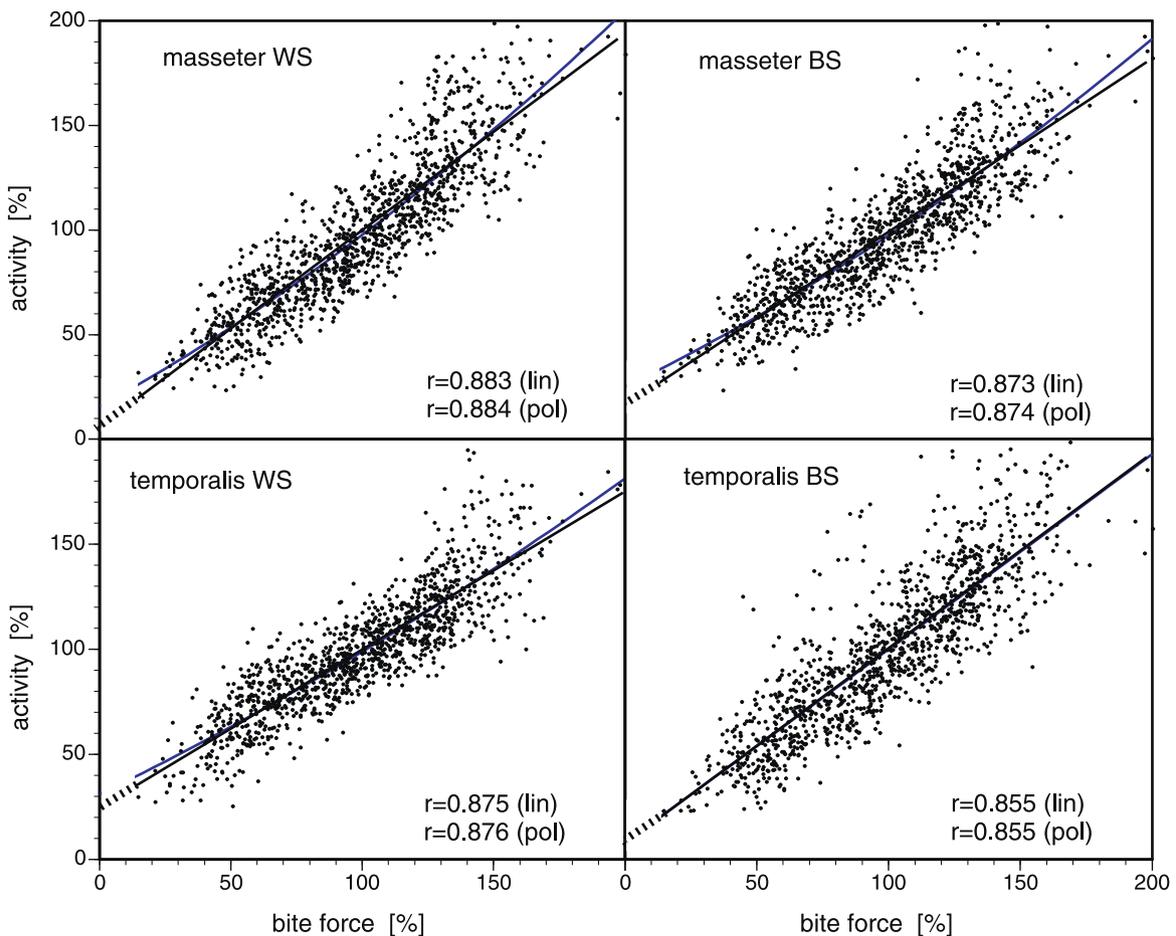


Fig. 2. Linear (lin) and polynomial (pol) regressions between the activities of the four muscles and the bite force performed on all bites. On the activity – and force axes, 100% indicates the individual mean value of each subject and each recording. The dotted lines indicate where the linear regression lines would intersect the *y*-axis.

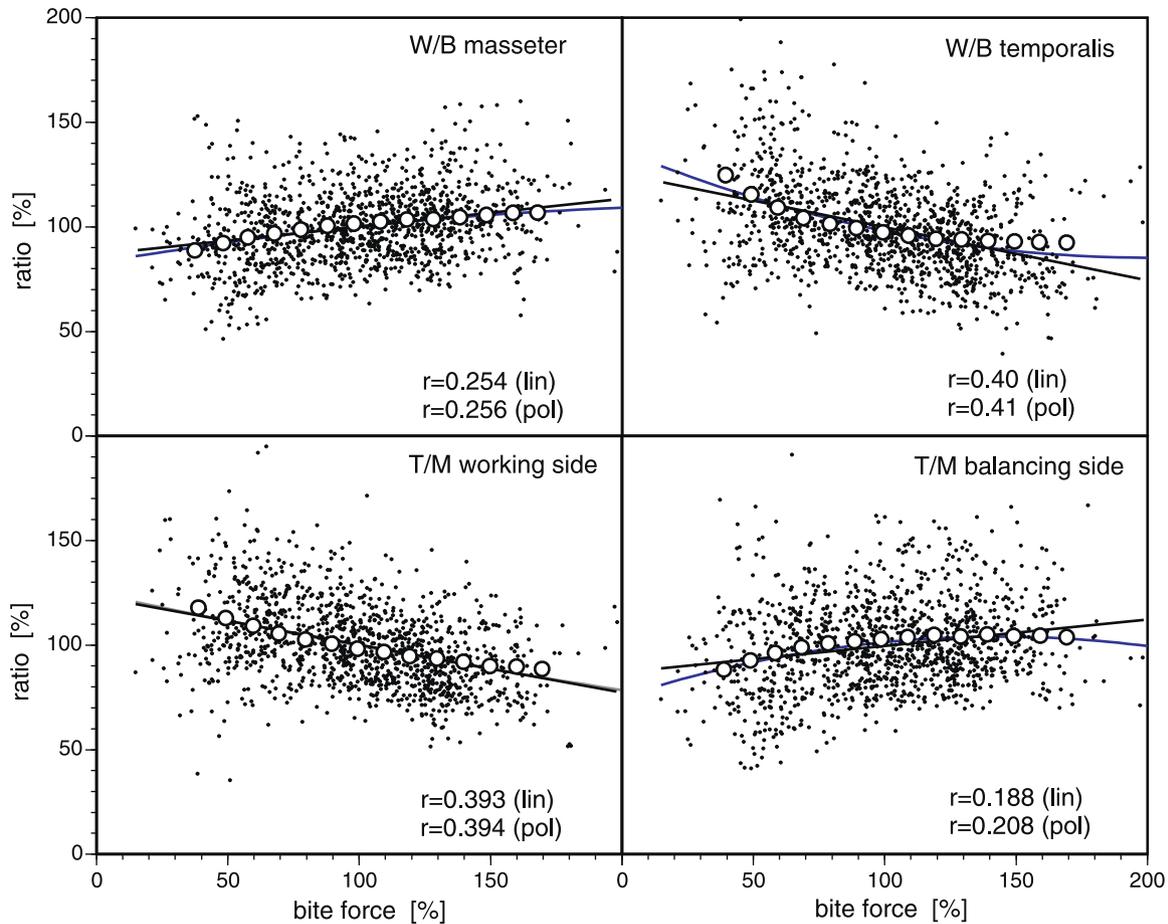


Fig. 3. Linear (lin) and polynomial (pol) regressions between the W/B and T/M-ratios and the bite force performed on all bites. On the ratios – and force axes, 100% indicates the individual mean value of each subject and each recording. The black circles represent activity ratios calculated from the 2nd order polynomial A/F_B regression curves shown in Fig. 2.

Table 1
Basic data of the linear regressions between normalized activity ratios and normalized bite force as shown in Fig. 3. SD – residuals indicates the standard deviation of the scatter of the ratios about the regression lines.

	W/B masseter	W/B temporalis	T/M WS	T/M BS
Slope	+0.13	−0.25	−0.24	+0.12
Intercept	86.60	125.00	124.00	88.00
r-Squared	0.06	0.15	0.16	0.04
SD – residuals (%)	17.20	20.00	18.90	21.60
p-Value	0.001	0.001	0.001	0.001

of the temporalis and the T/M-ratio on the WS decreased. This behavior is also reflected by ratios calculated from the polynomial regression curves of the A/F_B relations of Fig. 2. These calculated

Table 2
Relative frequencies and mean slopes of individual significant and non-significant correlations between activity ratios and bite force found within the subject group. For significant and non-significant correlations, the percentages and means slopes are itemized according to positive and negative correlations. All percentages refer to the total of 52 subjects.

Correlation	W/B masseter		W/B temporalis		T/M WS		T/M BS	
	%	Slope	%	Slope	%	Slope	%	Slope
Significant	35	0.22	54	−0.49	56	−0.47	40	0.22
Positive	25	0.46	8	0.35	4	0.38	25	0.73
Negative	10	−0.40	46	−0.62	52	−0.48	15	−0.42
Non-significant	65	0.12	46	−0.07	44	−0.08	60	0.02
Positive	48	0.19	12	0.22	17	0.17	33	0.20
Negative	17	−0.07	34	−0.17	27	−0.24	27	−0.20

ratios are shown in Fig. 3 as black circles in a range of 40–170% of the normalized bite force.

An overview on how the activity ratios were related to the bite force in single subjects is given in Table 2: Depending on the muscle, in 44–65% of the subjects activity ratios were not significantly correlated with the bite force while in 35–56% the correlation was significant. In cases with a significant correlation, the slopes of linear regressions were generally steeper than in cases with no significant correlation.

3.3. Variations of subject-controlled chewing-like force

When the subjects executed intermittent bites with uniform peaks corresponding to their individual chewing force, they

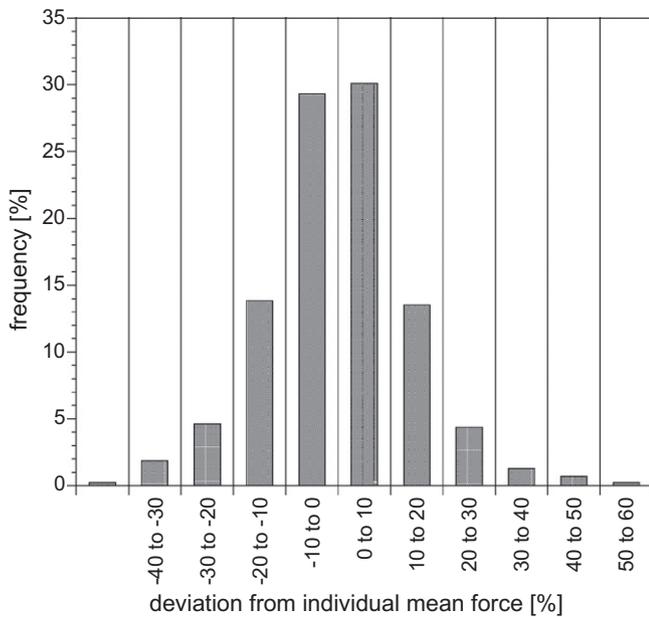


Fig. 4. Frequency distribution of all subjects' standardized deviations from the individual mean bite force when biting with self-assessed chewing-like force.

achieved a group mean bite force of 325 ± 61 N. The scatter about the individual mean bite force of each subject is shown in Fig. 4. The mean normalized standard deviation with respect to each subject's individual mean force amounted to 12.5%.

4. Discussion

The present results confirm significant but rather weak associations between activity ratios and bite force. Formally, these correlations are caused by the non-zero y -intercepts and the slight non-linearity of the A/FB relations. Mathematically W/B and T/M-ratios are equivalent to dividing activities within the A/FB regressions of two different muscles. If these regressions were linear with zero y -intercepts, the force on average would cancel out from the ratios. Group means of activity ratios would then correspond to the ratios of the slopes of the involved A/FB regressions and would be equal for all bite forces. In agreement with related studies (Pruim et al., 1978; Van Eijden et al., 1990; Lindauer et al., 1991) the y -intercepts of the A/FB regressions of all four muscles were positive (Fig. 3). Considered together with the slightly non-linear A/FB regressions, the bite force therefore does not necessarily cancel which leads to moderate association between ratios and bite force as displayed in Fig. 3. This explanation is well supported by the activity ratios shown in Fig. 3 that were calculated from the polynomial A/FB regressions of Fig. 2.

Physiological reasons for the observed associations between activity ratios and bite force are not obvious. Activity ratios could in principle be influenced by changing bite force directions or changing activation of differing muscle regions (Belsler and Hanam, 1986; Van Eijden et al., 1990; Mao and Osborn, 1994; Blanksma and Van Eijden, 1995; Rues et al., 2008). In order to be causative for the observed associations, these factors should change systematically during increase of the self-controlled bite force for which however there is no evidence. Another explanation based on biomechanical reasoning might be inferred from chewing studies: masseter W/B-ratios were found to be smaller with harder than with softer foods (Hylander et al., 1992; Blanksma and Van Eijden, 1995; Piacino et al., 2008) which suggested that stronger biting required a higher relative activation of the BS muscle

(Hylander et al., 1992; Blanksma and Van Eijden, 1995). If this assumption would apply, masseter W/B-ratios should have decreased with increasing bite force. In contrast however, the masseter W/B-ratio increased, i.e. the relative BS masseter activation decreased slightly with stronger biting (Fig. 3). This contradiction could be resolved by considering that activity ratios in isometric biting proved to be related to the jaw gap (Pröschel et al., 2008). Due to yielding of the bite fork, the initial jaw gap of 6 mm narrowed slightly when the bite force increased. Actually the slight changes of all four activity ratios (Fig. 3) correspond qualitatively to the trends observed in isometric biting with a stepwise reduced jaw gap starting at 6 mm (Pröschel et al., 2008). The jaw gap dependence of activity ratios could reconcile the present results with those of the cited chewing studies since harder foods were reportedly chewed with bigger jaw separations than softer ones (Hylander et al., 1992; Piacino et al., 2008). In view of present knowledge it appears that jaw gap is related to activity ratios in a consistent manner whereas bite force under the same experimental conditions shows conflicting relationships (Hylander et al., 1992; Blanksma and Van Eijden, 1995; Piacino et al., 2008; Pröschel et al., 2008).

Apart from the question of causality, the present results provide information on the suitability of subject control of bite force as an experimental method. In about 95% of all bites the chewing-like bite force varied within a range of $\pm 25\%$ (two standard deviations) around the individual mean bite force of the subjects. Because of the relationship between activity ratios and bite force, this scatter of bite force could entail a random scatter of group mean activity ratios. Since the A/FB regressions are approximately linear (Fig. 2), a change of group mean values of W/B- or T/M-ratios due to force scatter can be estimated from the slopes in Table 1. Accordingly a bite force variation of $\pm 25\%$ could be associated with a maximum variation of group mean activity ratios between $\pm 3\%$ (0.12 times 25%) for the BS T/M-ratio and $\pm 6.25\%$ (0.25 times 25%) for the W/B ratio of the temporalis in 95% of all bites. This variation is small compared to the residual scatter of activity ratios which ranged up to 21.6% (Fig. 3 and Table 1).

These findings may justify self control of bite force by subjects as an experimental method in cases where transducer-based force control is not feasible. Actually this applies to the vast majority of biting tests, in particular to those involving occlusal contacts or aiming to imitate conditions of natural mastication as closely as possible (Barbenel, 1974; Throckmorton et al., 1990; Erhardson et al., 1993; Fontijn-Tekamp et al., 2000; Proeschel and Raum, 2001; Iwasaki et al., 2003; Pröschel et al., 2008; Uchida et al., 2008; van der Bilt et al., 2008; Farella et al., 2008).

When subjects were asked to generate a chewing-like force, a group mean force of 325 ± 61 N was obtained which is similar to 322 ± 82 N achieved by another group of subjects who completed the same experimental protocol (Pröschel et al., 2008). This coincidence suggests that human motor control is able to transform a certain force perception acquired during chewing into a fairly reproducible isometric bite force. Because of a different sensory perception in transducer biting and in chewing, this self-assessed isometric force may have deviated from the actual chewing force. On the other hand, 325 N is a realistic magnitude for the chewing force of young males considering that chewing forces of up to 284 N were already achieved by elder implant patients (Mericske-Stern et al., 1992; Proeschel and Morneburg, 2002; Morneburg and Proeschel, 2003). The robustness of activity ratios against the variations of subject-controlled bite force supports the assumption that use of ratios obviates the need for transducer-based bite force control (Iwasaki et al., 2003). This may however not easily apply to single case analyses where the scatter of activity ratios may be bigger in cases with sporadic steep slopes of the ratio/force regressions (Table 2).

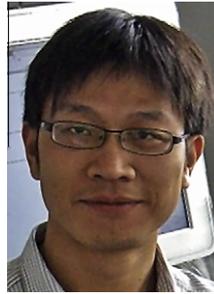
Summarizing, subject to the given experimental conditions, group mean values of activity ratios are weakly related to the bite force. For this reason, a limited scatter of bite force as entailed by subject control of force contributes marginally to the scatter of activity ratios. Hence ratios of activities evoked in unilateral biting with subject-controlled force appear to be relevant measures to study neuromuscular characteristics under conditions close to natural function.

Acknowledgement

This investigation was supported by Wilhelm-Sander-Foundation, Germany, Grant No. 2003.009.1.

References

- Bakke M, Micheler L, Han K, Möller E. Clinical significance of isometric bite force versus electrical activity in temporal and masseter muscles. *Scand J Dent Res* 1989;97:539–51.
- Barbenel JC. The mechanics of the temporomandibular joint – a theoretical and electromyographical study. *J Oral Rehabil* 1974;1:19–27.
- Belser UC, Hannam AG. The contribution of the deep fibres of the masseter muscle to selected tooth-clenching and chewing tasks. *J Prosthet Dent* 1986;56:629–35.
- Blanksma NG, Van Eijden TMGJ. Electromyographic heterogeneity in the human temporalis and masseter muscles during static biting, open/close excursions and chewing. *J Dent Res* 1995;74:1318–27.
- Erhardson S, Sheikholeslam A, Forsberg CM, Lockowandt P. Vertical forces developed by the jaw elevator muscles during unilateral maximal clenching and their distribution on teeth and condyles. *Swed Dent J* 1993;17:23–34.
- Farella M, Palla S, Erni S, Michelotti A, Gallo LM. Masticatory muscle activity during deliberately performed oral tasks. *Physiol Meas* 2008;29:1397–410.
- Faulkner MG, Hatcher DC, Hay A. A three dimensional investigation of temporomandibular joint loading. *J Biomech* 1987;20:997–1002.
- Ferrario VF, Sforza C. Biomechanical model of the human mandible in unilateral clench: distribution of temporomandibular joint reaction forces between working and balancing sides. *J Prosthet Dent* 1994;72:169–76.
- Fontijn-Tekamp FA, Slagter AP, van der Bilt A, van T Hof MA, Witter DJ, Kalk W, et al. Biting and chewing in overdentures, full dentures and natural dentitions. *J Dent Res* 2000;79:1519–24.
- Hylander WL, Johnson KR, Crompton AW. Muscle force recruitment and biomechanical modeling: an analysis of masseter muscle function during mastication in macaca fascicularis. *Am J Phys Anthropol* 1992;88:365–87.
- Iwasaki LR, Petsche PE, McCall WD, Marx D, Nickel JC. Neuromuscular objectives of the human masticatory apparatus during static biting. *Arch Oral Biol* 2003;48:767–77.
- Lindauer SJ, Gay T, Rendell R. Electromyographic-force characteristics in the assessment of oral function. *J Dent Res* 1991;70:1417–21.
- Mao J, Osborn JW. Direction of a bite force determines the pattern of activity in jaw-closing muscles. *J Dent Res* 1994;73:1112–20.
- Mericske-Stern R, Geering AH, Bürgin WB, Graf H. Three-dimensional force measurement on mandibular implants supporting overdentures. *Int J Oral Maxillofac Implants* 1992;7:185–94.
- Morneburg TR, Proeschel PA. In vivo forces on implants influenced by occlusal scheme and food consistency. *Int J Prosthodont* 2003;16:481–6.
- Piancino MG, Bracco P, Vallenga T, Merlo A, Farina D. Effect of bolus hardness on the chewing pattern and activation of masticatory muscles in subjects with normal dental occlusion. *J Electromyogr Kinesiol* 2008;18:931–7.
- Proeschel PA, Morneburg T. Task-dependence of activity/bite force relations and its impact on estimation of chewing force from EMG. *J Dent Res* 2002;81:464–8.
- Proeschel P, Raum J. Preconditions for estimation of masticatory forces from dynamic electromyograms and isometric bite force/activity relations of elevator muscles. *Int J Prosthodont* 2001;14:563–9.
- Pröschel PA, Jamal T, Morneburg TR. Motor control of jaw muscles in chewing and in isometric biting with graded narrowing of jaw gape. *J Oral Rehabil* 2008;35:722–8.
- Pruim CJ, Ten Bosch JJ, De Jongh HJ. Jaw muscle EMG activity and static loading of the mandible. *J Biomech* 1978;11:389–95.
- Rues S, Schindler HJ, Türp JC, Schweizerhof K, Lenz J. Motor behavior of the jaw muscles during different clenching levels. *Eur J Oral Sci* 2008;116:223–8.
- Throckmorton GS. Sensitivity of temporomandibular joint force calculations to errors in muscle force measurements. *J Biomech* 1989;22:455–68.
- Throckmorton GS, Groshan GJ, Boyd SB. Muscle activity patterns and control of temporomandibular joint loads. *J Prosthet Dent* 1990;63:685–95.
- Uchida S, Iwasaki LR, Marx DB, Yotsui Y, Inoue H, Nickel JC. Variations in activities of human jaw muscles depend on tooth-tipping moments. *Arch Oral Biol* 2008;53:199–205.
- Van der Bilt A, Tekamp FA, van der Glas HW, Abbink JH. Bite force and electromyography during maximum unilateral and bilateral clenching. *Eur J Oral Sci* 2008;116:217–22.
- Van Eijden TMGJ, Brugman P, Weijs WA, Oosting J. Coactivation of jaw muscles: recruitment order and level as a function of bite force direction and magnitude. *J Biomech* 1990;23:475–85.



Lei Chen received his bachelor degree in dentistry in 2001 and his master degree in 2004 from the School and Hospital of Stomatology of Wuhan University in China. From 2005 to 2007 he was working as a dentist at the School and Hospital of Stomatology of Beijing University under the guidance of Prof. Dr. Hailan Feng. From Sept. 2007 until March 2008 he joined Dr. Pröschel and Dr. Morneburg as a guest scientist at the Department of Prosthodontics of the Dental Clinic of Erlangen University. In August 2008, he received his Ph.D. degree from the School and Hospital of Stomatology of Beijing University. Dr. Chen has written several scientific articles about jaw movement simulation systems. He now works as a dentist at the China – Japan Friendship Hospital in Beijing.



Peter A. Pröschel received his Diploma in Physics from Erlangen University in 1975. One year later he joined the Department of Prosthodontics at the Dental Clinic of the University of Erlangen – Nürnberg where he supervised many of the department's scientific projects. In his spare time he wrote a thesis on astrophysics and obtained the degree of a Doctor of Physics (Dr. rer. nat.) and the position of an Associate Professor in 1981. He performed research on various biomechanical and physiological aspects of masticatory function including masticatory jaw movements, temporomandibular joint kinematics and occlusal interferences. In 1997 he received his Ph.D. degree and in 2003 the title of an Adjunct Professor. In the last five years he turned to the problem of relations between chewing force and muscle activity and to the physiological meaning of relative muscle activation. He is member of the International Association of Dental Research, the International College of Prosthodontics and other organisations and is author and co-author of about 60 scientific articles.



Thomas R. Morneburg graduated in Dentistry in 1985 and specialized in Prosthetic Dentistry in 1988 at the University of Erlangen – Nürnberg. In 2002 he obtained the Ph.D. degree at the University of Erlangen – Nürnberg. He was Assistant Professor at the Prosthodontic Department of the same university from 1985 to 2002. He is now Associate Professor and teaches "Evidence Based Dentistry". He is member of the German Society of Prosthodontics, the International Association of Dental Research, the International College of Prosthodontics and other organisations. His major field of research includes the physiology of mandibular movement and masticatory muscles, occlusal errors during manufacturing of dental restorations and success rates of microimplants. He has published more than 40 articles mainly in international journals.