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Original article

Impact of post-orthodontic dental occlusion on masticatory performance and chewing efficiency

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Summary

Background: Whether precise orthodontic detailing of occlusion impacts masticatory function is unknown. In this study, we aimed to assess the impact of post-orthodontic dental occlusion on masticatory performance and chewing efficiency.

Materials and methods: Fifty-four adults who completed orthodontic treatment were categorized into two groups using the American Board of Orthodontics (ABO) model grading system: one meeting ABO standards (ABO, $N = 29$), the other failing to meet them (non-ABO, $N = 25$). The electromyographic (EMG) signals of the anterior temporalis (AT) and superficial masseter muscles were recorded bilaterally during static (clenching) and dynamic (gum chewing) tests. Chewing efficiency was measured by calculating the median particle size (MPS) and broadness of particle distribution (BPD) after five chewing trials of experimental silicone food at a standardized chewing rate.

Results: Participants of the ABO group had a slightly more symmetric activation of the AT muscles during clenching ($P = 0.016$) and chewed a gum at a slower rate ($P = 0.030$). During the standardized chewing test with silicone food, ABO subjects had slightly greater EMG potentials at all muscle locations than non-ABO individuals (all $P < 0.05$). MPS and BDP did not differ significantly between groups (all $P > 0.05$).

Limitations. The severity of the initial malocclusion of the study participants was not in the statistical model as a potential confounder on the outcome measures.

Conclusions. Meeting ABO standards contributes to a slightly more balanced activation of the temporalis muscles during clenching and more efficient muscle recruitment during chewing but does not improve chewing efficiency.

Introduction

Comprehensive orthodontic treatment includes orthodontic finishing, the final stage of treatment focused on precise detailing of dental occlusion. With contemporary edgewise techniques, finishing is focused on optimization of occlusion and correction of any discrepancy between bracket prescription and position while accounting for individual tooth anatomy. Proper finishing can take a significant portion of the overall orthodontic treatment duration and is considered an important aspect of orthodontic treatment.

In 1999, the American Board of Orthodontics (ABO) implemented the dental cast and panoramic radiograph [ABO Cast-Radiograph (ABO-CR)] grading system for orthodontists seeking board certification by measuring the level of finishing in orthodontic cases (1, 2). The grading system evaluates the final alignment of teeth, the presence of rotation, occlusal contacts, interproximal contacts, the position of marginal ridges, occlusal relationships, and the buccolingual inclination of teeth, overjet, and root angulation. This method provides a score for measuring the quality of dental occlusion after orthodontic treatment (1). Both the American and European board standards are consistent with the descriptions of ideal and normal occlusion by Andrews (3). However, it may be questioned whether achieving an ideal occlusal relationship, as described by Andrews, is related to better masticatory performance and chewing efficiency—the ability to grind a certain portion of a test food during a given time.

Decreased masticatory performance or impaired chewing efficiency have been reported in subjects with dental malocclusion (4, 5). Ngom *et al.* (4) measured masticatory function and occlusal condition in 102 adults with no history of previous orthodontic treatment by measuring the particle size of chewed experimental food. Patients in 'definite-need' of orthodontic treatment (ICON score—Index of Complexity, Outcome and Need (6)—higher than 43) produced a larger median particle size than those who were considered to be in 'no-need' of orthodontic treatment (ICON score of 43 or below) when they were asked to chew test food made of condensation silicone. Similarly, English *et al.* (5) found that the ability to process and breakdown food is dependent on the type of malocclusion. In a sample of 185 subjects with no history of previous orthodontic treatment, the authors found that the median particle sizes for the Class I, Class II and Class III malocclusion groups were approximately 9%, 15% and 34% larger, respectively, than the normal occlusion group. Subjects with malocclusion reported chewing difficulties with fresh carrots or celery and firm meat (5). Alterations in masticatory movement (7–10) and masticatory muscle activity (11–15) have been documented in individuals with malocclusions as well. For instance, masticatory muscle activity during chewing was found to be less coordinated in Class III (16) and Class II (17) subjects. Bakke *et al.* (18) reported a positive correlation between occlusal stability—indicated by the number of teeth in physical contact and the number of opposing pairs of teeth in contact in intercuspal position and lateral contact position—and shorter contraction time and larger electromyographic (EMG) potentials during chewing. The aforementioned studies support the association between occlusal factors and masticatory performance and suggest that they are influenced by the type of malocclusion. Based on these findings, superior orthodontic finishing, resulting in improved post-orthodontic dental occlusion, should be associated with better masticatory performance and chewing efficiency. However, whether excellent orthodontic occlusal detailing has a significant impact on these features is still unknown.

This study aims to evaluate the impact of post-orthodontic dental occlusion on masticatory performance and chewing efficiency. The null hypothesis to be tested is that 'excellent' and 'poor' orthodontic detailing, as measured *via* the ABO-CR score system, have a similar impact on masticatory performance and chewing efficiency. The results of this research may provide, for the first time, scientific evidence to support the need for high-quality finishing standards before patient discharge.

Materials and methods

Study sample

The study was approved by the Research Ethics Board of University of Toronto (ID #35047). All subjects signed an informed consent prior to their participation. The experimental procedures were performed at the Centre for Multimodal Sensorimotor and Pain Research at the Faculty of Dentistry, University of Toronto.

Participants were recruited from the University of Toronto Graduate Orthodontics Retention Clinic and the student population of the University of Toronto, Faculty of Dentistry. Eligible participants were over 18 years of age, in good health and had completed comprehensive orthodontic treatment (either with fixed appliance or clear aligners) by an orthodontic specialist minimum at least 6 months prior to the participation in the study. Participants completed a dental and medical history questionnaire and the Temporomandibular Disorder Pain Screening Questionnaire (19) to verify their eligibility. Exclusion criteria were orthodontic treatment provided by a non-orthodontic specialist, temporomandibular disorders according to the Diagnostic Criteria for Temporomandibular Disorders (20), use of pacemaker, neuromotor deficiencies or any neurological illness, medication affecting neuromuscular activity, orthognathic surgery as reported by patients on the health history form, edentulous area within the dental arch (with the exception of third molars), and refusal to participate in the study.

Written and verbal informed consent was obtained from 54 subjects [27 males and 27 females; mean age 26.3 years; standard deviation (SD) = 4.8 years]. Participants were assigned an identification number and all collected data were anonymized prior to evaluation.

ABO-CR assessment of orthodontic study models

Alginate impressions (Hydrogum, Zhermack Dental, Italy) were taken to fabricate orthodontic study casts (orthodontic plaster, Super white, Whip-Mix Corporation, Louisville, KY, USA). The participants' occlusion was recorded with wax (C/D #2 pink baseplate wax, Central Dental Ltd, Canada). The orthodontic models were graded by one operator (JS) in a random order after being calibrated using the ABO calibration kit (21) and following the guidelines available on the ABO website (1). The validity of the ABO-CR Evaluation has been previously tested (22). The study evaluation omitted the radiographic evaluation of root angulation component in order to eliminate unnecessary radiation exposure (23). Participants were divided into two groups according to their ABO score using 27 as a cut-off value. The ABO group (N = 29; 16 females and 13 males) had ABO scores less than or equal to 27, which is the maximum score the ABO would consider for an orthodontic case to be determined 'complete' for the ABO-CR Evaluation (1). The non-ABO group (N = 25; 11 females and 14 males) had ABO scores greater than 27, considered unacceptable as they failed to meet the ABO standards. Twenty study casts were randomly selected using a computer-generated random number sequence and graded for intraoperator reliability test 3 months after initial model analysis.

Experimental procedures

Participants were submitted to two experimental sessions, during which the EMG activity of the right and left anterior temporalis (AT) and superficial masseter (SM) muscles were recorded as per below. All participants sat in a dental chair with their head unsupported (18). The position of the back of the dental chair was fixed and the headrest was removed. The EMG recordings were performed by a single examiner (JS) who received extensive training in electromyography prior to performing the experiments.

In the first session participants were asked to:

1. Clench their teeth as hard as possible for 5 seconds to record maximum voluntary contraction (MVC) in intercuspal position (static test);
2. Clench their teeth at MVC on 10 mm thick cotton rolls (Quala Dental Products, Nashville, TN, USA) positioned along the occlusal surface of mandibular posterior teeth on each side (from first premolar to molars) for 5 seconds (for calibration);
3. Chewed a gum (Trident fresh mint flavor, Mondelez International, USA) on the right side for 15 seconds and the left side for 15 seconds (dynamic test).

These standardized tasks follow a protocol developed by Ferrario *et al.* (24) and allow to compute EMG indices of muscle activity. In the second session, participants were asked to chew a standardized experimental silicone food. The median particle size (MPS) and broadness of particle distribution (BPD) of the pulverized food bolus were computed to estimate chewing efficiency (see particle size analysis paragraph).

Surface electromyography

The skin was cleaned prior to electrode placement with alcohol to reduce skin impedance. Male participants were asked to shave prior to the experiment. Disposable square silver–silver chloride bipolar surface pre-gelled electrodes (Kendall, Mansfield, MA, USA) with a width of 22 mm were placed on the skin along the main direction of the muscular fibers (24). For AT, the electrodes were vertical along the anterior margin of the muscle (about on the coronal suture). For SM, they were parallel to the muscle fibers, with the upper pole of the electrode at the intersection between the tragus-labial commissure and the exocanthion–gonion lines (25). A wireless EMG device (TMJOINT, BTS S.p.a., Garbagnate Milanese, Italy) was attached to the electrodes in order to record, amplify and filter (low-pass filter 500 Hz; high-pass filter 10 Hz). The EMG signals were sampled at 1 kHz.

Dental Contact Analyser software (BTS S.p.a., Garbagnate Milanese, Italy) was used to process the raw electrical signals to standardized EMG indices (26). The software algorithm compared the relative activity of various muscle couples and produced the following standardized EMG indices:

1. Percentage of overlapping coefficient (POC, %) compares the overlapping activity between the left and right muscle pairs during MVC on intercuspal position (26). POC of 100% indicates perfect symmetry in muscle contraction and 0% indicates the absence of concurrent activation of paired muscles. Normal values range between 85% and 100% (24, 27, 28). POC was reported for the AT muscle (POC AT), SM muscle (POC SM) and both muscles combined (POC mean).
2. Torque coefficient (TC, %) compares the overlapping activity between the controlateral couples of AT and SM muscles. The contraction of the AT muscle moves the mandible upwards and backwards while the SM muscle moves the mandible upwards and forwards (24). For example, a greater activity of the right AT and left SM couple over the left AT and right SM couple results in a torqueing or latero-deviating effect on the lower jaw towards right (26). TC of 0% indicates no symmetry in activation of the couples and the greatest torquing effect while 100% indicates perfect symmetry and no torquing effect. Normal values range between 90% and 100% (24, 27, 28).
3. Antero-posterior coefficient (APC, %) compares the overlapping activity between the AT and SM muscles bilaterally. The APC of 0% indicates unbalanced activity between the AT and SM muscles, whereas 100% indicates well-comparable activity of the muscles (28). Greater activity of the AT muscle displaces the resulting vector of the occlusal forces during clenching forward, whereas greater SM muscle activity would cause its backwards displacement. Normal range is between 90% and 100% (28, 29).
4. Total standardized muscle activity (IMPACT) represents the integrated area of the EMG standardized potentials of both AT and SM muscles over the total 5 second period (26). Smaller values indicate that the EMG standardized potentials were reduced during the MVC on intercuspal position and that maximal EMG activity could not be expressed. Normal values range between 85% and 115% (28). For the dynamic test, IMPACT was reported as the average of right- and left-sided gum chewing for AT and SM muscles (IMPACT AT and IMPACT SM, respectively).
5. Frequency index (FREQ, Hz or chewing cycle per second) measures the frequency of masticatory cycles during chewing a gum. FREQ is averaged for right- and left-sided chewing.

Particle size analysis

CutterSil® (Kluzer, USA), a condensation silicone impression material, is considered standard test food for evaluating chewing efficiency (30–36). The standardized production of test food followed the protocol by Alberta *et al.* (35). Twenty millimetre diameter holes were drilled into a 5 mm thick Plexiglas template. According to the manufacturer's instruction, 14.4 g of CutterSil® putty and 0.21 g of CutterSil® hardener universal plus paste (Kluzer, USA) were kneaded and molded into the template. Excess material was removed. After setting, round silicone tablets were removed and cut into quarters. Five portions containing three quarter-tablets were packaged for each participant (32). Each sample weighed approximately 10 g.

Participants performed five chewing sequences interspersed with a 2 minute rest period. Each sequence consisted of chewing three CutterSil® quarter-tablets for 20 cycles at a rate of 1.33 Hz (80 beats per minute), considered habitual chewing rate (32, 33). The EMG activity of the AT and SM was recorded bilaterally using the same EMG device described above. A digital metronome was played in the background and participants were asked to chew to the beats of the metronome. Participants were instructed to expectorate the bolus into a container containing a filter paper supported by a funnel and rinse out the residual silicone fragments into the same container using water. Once the filtration was complete, the filter paper and CutterSil® pieces were air dried, then heat dried for 1 hour at 80°C in a convection countertop oven (Black & Decker, USA) (32, 33, 37). Dried CutterSil® particles were weighed again and separated according to their size using a series of seven sieves in order of decreasing mesh size—5.6, 4.0, 2.8, 2.0, 0.850, 0.425 and 0.250 mm (Laval Lab Inc., Canada)—stacked on a dental vibrator for 2 minutes at a constant vibration intensity (4, 30, 32–34). The contents on each sieve were weighed to the nearest 0.01 g with a precision balance (EJ-610 scale, A and D Engineering, USA).

Given the size of the sieve aperture and the cumulative weight of the sample that could pass through each successive sieve, MPS and BPD were estimated based on the Rosin–Rammler equation (38–40):

$$Q_w = 100\left[1 - 2^{-\left(\frac{x}{x_{50}}\right)^b}\right]$$

Q_w is the cumulative weight percentage of particles with a diameter smaller than x (the maximum sieve aperture), x_{50} is the MPS and b describes the BPD. MPS represents a theoretical sieve aperture through which 50% of the total weight of the particle can pass. It describes the central tendency of the sieved particles where the higher value corresponds to decreased chewing efficiency and smaller values to increased chewing efficiency. A higher value for b corresponds to cumulative weight percentage curves with steeper slopes and, thus, narrower distribution of the particle size.

Self-perceived masticatory function

Participants rated their own masticatory function using a modified Self-Assessment of Chewing Function Questionnaire by Persic *et al.*, which was demonstrated to be reliable, valid, and responsive (41). The questions are reported in Table 1.

A modification of the 100 mm visual analogue scale (VAS) delimited by 'strongly disagree' and 'strongly agree' anchors was applied in order to assign a metric value (VAS score) to each response based on the distance of the marked response from the left anchor of the line (strongly disagree) (41). Participants were compensated with \$30 CAD cash at the end of the experiment with an additional \$10 CAD for those who incurred additional indirect cost (i.e. public transit fare or parking cost).

Statistical analysis

Data were first checked for normal distribution using the Kolmogorov–Smirnov test. Normally distributed data were reported as means and SDs. Data without normal distribution were reported as medians and interquartile ranges [IQR]. Between-group differences for standardized EMG indices, MPS, BPD and VAS scores were investigated using Mann–Whitney *U*-test or unpaired *t*-test. Stepwise linear regression (on transformed data) was completed for select outcome measures with significant difference between the groups to determine which of the components of the ABO-CR evaluation, if any, may explain variation in the outcome measure. Intraoperator reliability was determined for the assessment of the ABO-CR scores by computing intraclass correlation coefficients (ICCs).

The root mean square (RMS) and the median power frequency (MDF) of the EMG signals recorded during the silicone chewing test from the AT and the SM of both sides were computed. Mixed-effect models were used to test between-group differences in RMS and MDF amplitudes. *Post hoc* comparisons were adjusted using the Bonferroni method. Data were analyzed with SPSS 24.0 (IBM Corp. Released 2016. IBM SPSS Statistics for Windows, Version 24.0. Armonk, NY: IBM Corp.). Data analysis was performed by a single operator (IC) who was blinded to the allocation of participants to study groups. The statistical significance level was considered when $P < 0.05$.

Table 1. Modified self-assessment of Chewing Function Questionnaire (41)

1. Have you had any difficulty chewing apples/raw carrots or foods of similar consistency?
2. Have you had any difficulty chewing bacon/smoked ham/backed or fried firm meet or foods of similar consistency?
3. Have you had any difficulties chewing biscuits, crackers, tea biscuits or foods of similar consistency?
4. Have you had any difficulty chewing fresh bread, doughnut or foods of similar consistency?
5. Have you had any difficulty chewing nuts/walnuts/almonds/macadamias/peanuts or similar food?
6. Have you had any difficulty chewing lettuce, raw cabbage or similar food?
7. Have you felt insecure when you are chewing?
8. Have you had any difficulty when biting different foods (food incision)?
9. Have you noticed food catching or food remaining stuck between or on your teeth during or after meals?
10. Have you had any difficulty chewing a chewing gum?

Participants of both the ABO and non-ABO groups answered to each of the following questions by drawing a vertical line on a 100 mm Visual Analogue Scale (left anchor: 'strongly disagree'; right anchor: 'strongly agree').

Sample size calculation

Sample size calculation was completed for two outcome measures. The first was POC (see Surface electromyography) for the AT muscle during surface electromyography. Ferrario *et al.* (24) reported the mean POC for AT in their control group consisting of Angle Class I canine and molar relationship as 89.34% (SD = 3.9%). A mean difference of 4% could be considered clinically relevant as this represented 1 SD from the mean. The sample size needed to detect such difference between two groups (two-tailed two-sample *t*-test; $\alpha = 0.05$ and $1 - \beta = 0.9$) was 21 subjects in each group.

Second, the sample size was calculated based on the MPS for standard food test. Based on the two-sided two-sample *t*-test, the sample size required in each group in order to detect at least 1 mm^2 difference in MPS assuming equal sample size in each group using the findings from Ngom *et al.* (4) at a significance level of 0.05 and with 80% power is 19. Testing for a difference in MPS lower than 1 mm^2 may be of limited clinical significance. Therefore, a sample size of 21 subjects in each group was determined to be adequate for the purpose of the study.

Results

The intraoperative reliability test reported excellent reliability for the ABO-CR scores (ICC = 0.90; 95% confidence interval: 0.75–0.96) (42). The mean ± SD ABO-CR score of the entire study sample was 27.2 ± 8.8 (range 12–47). The mean ABO-CR score of the ABO group ($N = 25$) was 20.7 ± 4.3, while the non-ABO group ($N = 29$) had a mean ABO-CR score of 34.8 ± 6.3.

Descriptive statistics for EMG indices are reported in Table 1. The analysis of the EMG indices revealed statistically significant differences between the ABO and non-ABO group for POC AT and FREQ (Table 2). The median POC AT [IQR] was greater in the ABO group (86.6 [4.3] %) than the non-ABO group (84.4 [13.1] %; $P = 0.016$). The mean FREQ (right and left combined) was smaller in the ABO group 1.5 ± 0.2 Hz than the non-ABO group (1.7 ± 0.2 Hz; $P = 0.030$). There were no between-group differences for median APC, IMPACT, IMPACT SM and IMPACT AT (all $P > 0.05$, Table 2).

The particle size analysis was based on 50 subjects. The ABO group had 24 subjects and the non-ABO group 26 subjects. Data from four subjects were removed due to incomplete data ($N = 1$), an inconsistency in the weight of the sample (more than 5% change in weight) during the experiment ($N = 1$) and the lack of data points required for the Rosin–Rammler equation ($N = 2$; i.e. no CutterSil® particle passed through the first sieve).

The median chewing rate during the silicone chewing test did not differ between groups (ABO 1.35 [0.05] Hz; non-ABO 1.35 [0.05] Hz, $P = 0.500$; Figure 1). The RMS amplitudes for all muscles were greater in the ABO than non-ABO group (all $P < 0.05$; Figure 1B), whilst there were no between-group differences in MDF (all $P > 0.05$; Figure 1C). The mean RMS and MDF trajectories of all muscles within each group during the five trials are reported in Figures 2 and 3. Neither MPS nor BPD was different between ABO groups (all $P > 0.05$).

Table 2. Comparison of standardized EMG indices, particle traits and responses from the questionnaire between the ABO and non-ABO groups. ABO: American Board of Orthodontics; BPD: broadness of particle distribution; EMG: electromyographic; MPS: median particle size; VAS: Visual Analogue Scale

	Index	ABO	Non-ABO	*P* value
EMG indices static test (%)	POC AT	86.6 [4.3]	84.4 [13.1]	**0.016**
	POC_SM	86.4 [8.0]	85.3 [4.7]	0.190
	TC	90.5 [3.3]	89.8 [5.7]	0.089
	APC	87.4 [15.1]	86.3 [19.2]	0.310
	IMPACT	61.1 [42.4]	49.6 [22.4]	0.143
EMG indices dynamic test	Frequency (Hz)	1.5 ± 0.2	1.7 ± 0.2	**0.030**
	IMPACT AT (%)	84.7 [72.1]	87.6 [133.6]	0.748
	IMPACT SM (%)	48.9 [81.6]	59.5 [58.4]	0.742
Particle size analysis	BPD	2.96 [1.45]	3.30 [1.78]	0.319
	MPS	7.35 ± 2.39	8.24 ± 2.69	0.650
Self-report VAS score (mm)	Q1	4 [7]	1 [13]	0.151
	Q2	5 [23]	1 [16]	0.277
	Q3	2 [11]	0 [3]	0.121
	Q4	1 [10]	0 [3]	0.136
	Q5	3 [16]	0 [5]	**0.032**
	Q6	2 [10]	0 [3]	0.138
	Q7	2 [12]	1 [9]	0.582
	Q8	3 [12]	3 [18]	0.677
	Q9	47 [55]	31 [47]	0.425
	Q10	2 [15]	0 [6]	0.284
	Q Total	121 [157]	6 [103]	0.472

Medians and interquartile ranges [IQR] were reported for non-normally distributed measures. Means and standard deviations (±SD) were reported for data with normal distribution. Statistical significance was considered when $P < 0.05$ (in bold).

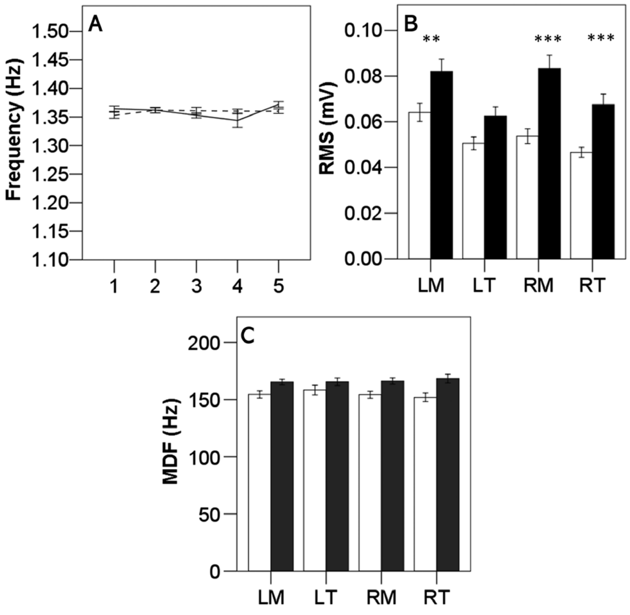

Figure 1. (A) Mean chewing frequency rate, (B) mean root mean squares (RMS) and (C) mean median power frequency (MDF) during the silicone chewing test (five trials) in the ABO (solid line/black bars) and non-ABO (dotted line/white bar) groups. The error bars indicate the standard errors of the mean. **Between-group significant differences at $P < 0.005$). ***Between-group significant differences at $P < 0.001$.

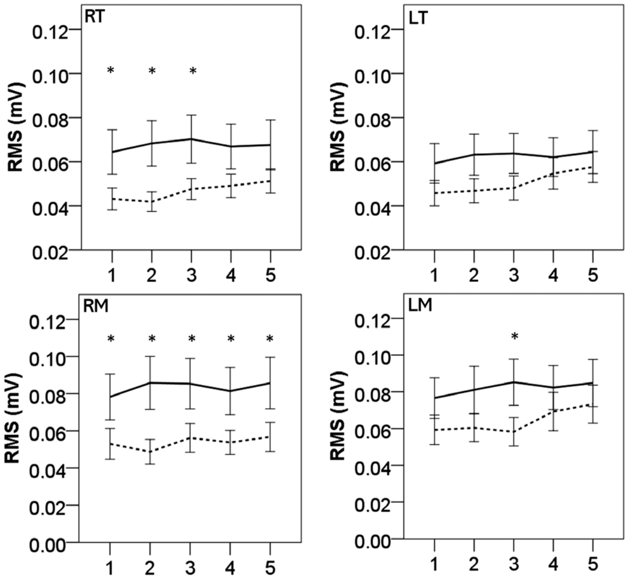

Figure 2. Mean root mean square (RMS) trajectories during the silicone chewing test (five trials) in the ABO (solid line) and non-ABO (dotted line) groups. RT: right anterior temporalis; LT: left anterior temporalis; RM: right superficial masseter; LM: left superficial masseter. The error bars indicate the standard errors of the mean. *Between-group significant differences at $P < 0.05$.

The responses from the questionnaire did not reveal any statistically significant difference (all $P > 0.05$) between the groups except for Q5 (chewing difficulty with nuts) (Table 1). The ABO group reported median VAS score of 3 [16] mm, while the non-ABO group reported 0 [5] mm (P = 0.032).

POC AT and FREQ were included as dependent variables in a stepwise linear regression model, which used ABO-CR components as predictors. POC AT data were transformed to obtain normal distribution. Among the seven components of the ABO-CR evaluation considered, only *occlusal contact* was a statistically significant

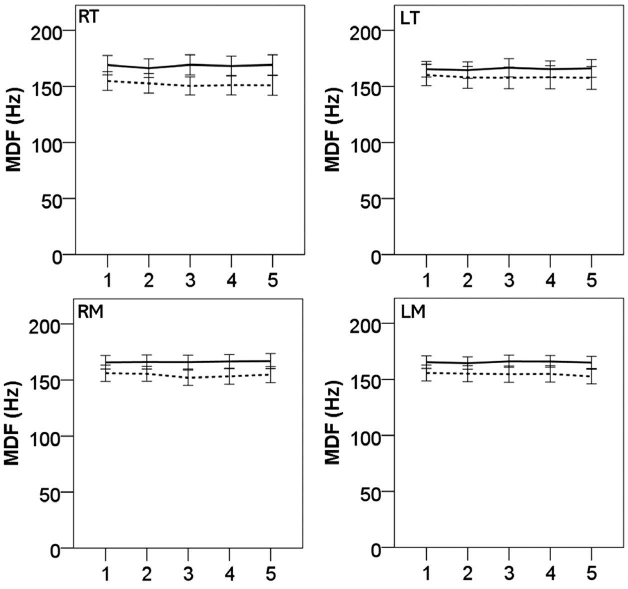

Figure 3. Mean median power frequency (MDF) trajectories during the silicone chewing test (five trials) in the ABO (solid line) and non-ABO (dotted line) group. RT: right anterior temporalis; LT: left anterior temporalis; RM: right superficial masseter; LM: left superficial masseter. The error bars indicate the standard errors of the mean. No between-group differences in each of the trials were found at $P < 0.05$.

explanatory variable ($P = 0.044$, Table 3). The *B* coefficient for *occlusal contact* was –0.805 (standard error = 0.389).

Discussion

This study aimed to provide new knowledge on the relationship between masticatory performance and occlusion in healthy adults who completed orthodontic treatment. While the quality of orthodontic finishing is often claimed to be crucial for occlusal stability and proper masticatory function, no previous study has tested the impact of post-orthodontic minor occlusal discrepancy on masticatory performance. The standardized EMG protocol used in this study to compute EMG indices is considered to be reliable and repeatable (24, 28, 43–44). The information provided by the standardized EMG indices allows for direct comparisons between subjects (24) and is clinically relevant (26). The EMG protocol used in this study has been widely used previously (24, 27–29).

The key finding from the assessment of the EMG indices of the AT and SM muscles during MVC (static test) was that the ABO group demonstrated a higher median POC AT with a narrower IQR (86.6 [4.3] %) compared to the non-ABO group (84.4 [13.1] %). In other words, the individuals with better occlusal details displayed a slightly more balanced activation of the AT muscle couple during MVC (tooth clenching). The median POC AT for the non-ABO group was close to but below the normal value, which ranges between 85% and 100% (24, 27, 28). Moreover, while chewing a gum, the chewing rate of the ABO group (FREQ) was slightly lower than the non-ABO group, which suggests that participants in the non-ABO group had to chew faster to soften the gum. In addition, the greater RMS amplitude of the EMG signals during the silicone chewing test could indicate that the pattern of masticatory muscle contraction of the ABO group slightly more efficient than the non-ABO group. It is likely that, while chewing the same silicone food at the same rate, individuals with better occlusal relationship recruited more muscle fibers and/or their muscle fibers contracted more. Although not significant, the MDF was slightly lower in the non-ABO group during the five chewing trials, which could indicate some muscle fatigue in these participants.

Table 3. Stepwise linear regression for percentage overlapping coefficient values of the anterior temporalis

	Unstandardized coefficients		Standardized coefficients		
Model	*B*	Std. Error	Beta	*t*	Sig.
Constant	84.440	1.928		43.791	<0.001
Occlusal contacts	−0.805	0.389	−0.278	−2.067	**0.044**

Statistical significance was considered at $P < 0.05$ (in bold).

Ferrario *et al.* (28) analyzed between-group differences in their 62 subjects with full natural dentition when they were categorized as either in 'complete' Class I relationship for all canines and molars or in 'partial' Class I relationship. While there was no discernable mean difference in POC AT, POC SM and TC between the groups, the 'complete' Class I group demonstrated lower coefficient of variation (percentage ratio of SD to mean) for POC AT compared to the 'partial' Class I group. A similar pattern was observed in our data where the ABO group demonstrated smaller IQR (4.3%) for POC AT compared to the non-ABO group (13.1%). The presence of group differences in POC AT but not POC SM suggests that the coordination of temporalis muscle activity may be more sensitive to small alterations in the occlusion as reported by Wang *et al.* in a previous study (45). The stepwise regression analysis showed that occlusal contacts best explain the changes in POC AT. Better occlusal contacts were associated with a more balanced activation of the AT muscles. This finding is in agreement with a previous study, in which subjects with reduced number of teeth with physical contact showed decreased EMG potential during chewing (18). The greater EMG potentials during the silicone chewing test in the ABO group confirm previous studies that have indicated that subjects with poor occlusion tend to present with decreased EMG potentials (16, 18, 46, 47).

Our study demonstrated that there was no discernible group difference for median particle size and broadness of particle distribution, suggesting that the chewing efficiency may not be affected by the quality of occlusal details after orthodontic treatment or by minor discrepancies in dental occlusion. Direct comparison with other studies can be difficult because of differences in the preparation of the test food and experiment protocols. The literature suggests that chewing efficiency may be impacted by clinically relevant malocclusion. Ngom *et al.* (4) reported subjects in definite need for orthodontic treatment—ICON score higher than 43—produced significantly larger median particle size of 4.03 mm^2 compared to 3.46 mm^2 from those who were categorized as not needing orthodontic treatment (ICON score of 43 or less). Similarly, English *et al.* (5) reported that Class I, Class II and Class III malocclusion groups produced larger median particle sizes—3.6, 3.8 and 4.4 mm^2, respectively—compared to the Class I normal occlusion group (MPS = 3.3 mm^2). Owen *et al.* (34) inferred an indirect association between malocclusion and MPS. In their study, Class I, Class II and Class III malocclusion groups exhibited decreasing magnitude of interocclusal contact and near contact (<350 µm) surface area where the Class III malocclusion group was described to have the smallest area of contact and near contact; decreased contact and near contact area was, in turn, associated with increased MPS and BPD. They reported that a statistically significant relationship was detected when the area of contact and near contact area within 250 µm was considered (34). Therefore, it is possible that the standardized experimental chewing test used in this study may not be sensitive enough to detect the impact of minor occlusal discrepancies on chewing efficiency. Nonetheless, our sample size calculation was based on a 1 mm^2 difference in mean particle size between groups. It is our opinion that a difference of less than 1 mm^2 is clinically not relevant.

The original Self-Assessment of Chewing Function Questionnaire developed by Persic *et al.* (41) used a five-point Likert scale (0–4) where a higher score indicates severe problems with chewing. The questionnaire was developed using a varied sample population, including patients with previous prosthodontic treatment, dental students, patients with natural teeth, removable denture wearers and patients with prosthodontic treatment needs. The questionnaire was demonstrated to be reliable, valid and responsive (41). In our study, a modification of a 100 mm long VAS (delimited by 'strongly disagree' and 'strongly agree') was applied to increase the sensitivity of detecting potential difference among full dentate participants (5, 48). The responses from the questionnaire showed that neither the ABO nor the non-ABO group reported having chewing difficulties with different common foods, including apple or carrots (Q1), meat or bacon (Q2), biscuits or crackers (Q3), fresh bread (Q4), different nuts (Q5), lettuce or raw cabbage (Q6) and chewing gum (Q10). Furthermore, they denied feeling insecure during mastication (Q7) and denied having difficulties with biting food (Q8). Although the ABO group reported differently from the non-ABO group for Q5 ($P = 0.032$), the group difference is minimal and clinically irrelevant (median VAS for the ABO group = 3 mm; non-ABO group = 0 mm). English *et al.* (5) found that their normal occlusion control group reported significantly greater ability to chew fresh carrots and celery than all malocclusion groups and steak and other firm meats better than the groups with Class II and Class III malocclusion. Henriksen *et al.* (48) reported that the normal occlusion group rated their masticatory ability more favorably than either of the Class II malocclusion groups whether they were scheduled to receive orthodontic treatment or not. While malocclusion appears to impair patients' perception of their masticatory ability, the quality of occlusal details after orthodontic treatment did not impact self-evaluation of chewing ability in our study significantly.

The limitations of the study design warrant a cautious interpretation of the results. In our study, it was not possible to distinguish between occlusal finishing, occlusal settling and relapse, but this, on the other hand, increased the external validity of our study findings because our sample population was representative of the broader orthodontic patient population who are treated by different orthodontic specialists for various types of initial malocclusion with different levels of finishing, occlusal settling and relapse. While small occlusal discrepancies were measured according to the ABO-CR evaluation criteria, the type and severity of the participants' initial malocclusion were unknown and not included in the statistical models as potential confounders. Whether the severity of initial malocclusion affects the quality of occlusion after orthodontic treatment is controversial. Vu *et al.* (49) reported that while the severity of initial malocclusion, according to the discrepancy index by ABO, was a sensitive prospective indicator of treatment duration, the treatment outcomes according to the ABO-CR evaluation was independent of treatment duration. On the other hand, Cansunar *et al.* (50) reported the severity of initial malocclusion had *some* impact on the ABO-CR score. While the discrepancy index they computed was not associated with the ABO-CR score, their multivariate regression test between the subcomponents of the discrepancy index and ABO-CR score revealed that the initial overbite, lateral open bite, crowding and buccal posterior crossbite had significant impact on the ABO-CR score. Pulfer *et al.* (51) reported a weak correlation between the discrepancy index and ABO-CR components ($r = 0.17$) in their 7-year retrospective study containing 716 patients with routine malocclusions. They concluded that treatment outcome was more dependent on treatment duration and on patient cooperation than on the complexity of the malocclusion for most patients. Therefore, it is possible that the severity of malocclusion of our research participants could have affected the quality of post-orthodontic dental occlusion and impacted participants' masticatory performance and chewing efficiency. Thus, whether the severity of initial malocclusion affects masticatory performance and chewing efficiency after orthodontic treatment should be explored also in further studies with a prospective design.

Conclusion

Our study demonstrated that post-orthodontic dental occlusion meeting ABO standards contributes to more balanced activation of the AT muscle during function but does not impact chewing efficiency—i.e. the ability to breakdown experimental food—or self-perception of chewing ability. Whether the minor differences in the EMG activity of the muscles have a clinical impact, or whether they may predispose to the onset of masticatory disorders, is unknown. Therefore, future studies are still needed to inform the orthodontic community about the impact of post-orthodontic dental occlusion on masticatory function. Future studies in this area will strengthen the scientific evidence for the functional benefits of orthodontic treatment and inform the American and European boards on establishing board standards that orthodontic specialists should strive to achieve.

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Conflict of interest

The authors declare no conflict of interest.

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