The effect of food bolus location on jaw movement smoothness and masticatory efficiency


Abstract
Masticatory efficiency in individuals with extensive tooth loss has been widely discussed. However, little is known about jaw movement smoothness during chewing and the effect of differences in food bolus location on movement smoothness and masticatory efficiency. The aim of this study was to determine whether experimental differences in food bolus location (anterior versus posterior) had an effect on masticatory efficiency and jaw movement smoothness. Jaw movement smoothness was evaluated by measuring jerk-cost (calculated from acceleration) with an accelerometer that was attached to the skin of the mentum of 10 asymptomatic subjects, and acceleration was recorded during chewing on two-colour chewing gum, which was used to assessed masticatory efficiency. Chewing was performed under two conditions: posterior chewing (chewing on molars and premolars only) and anterior chewing (chewing on canine and first premolar teeth only). Jerk-cost and masticatory efficiency (calculated as the ratio of unmixed azure colour to the total area of gum, the unmixed fraction) were compared between anterior and posterior chewing with the [...]
The effect of food bolus location on jaw movement smoothness and masticatory efficiency

W. N. B. MOLENAAR*, P. J. GEZELLE MEERBURG*, J. LURASCHI†‡, T. WHITTLE†, M. SCHIMMEL‡, F. LOBBEZOO*, C. C. PECK†, G. M. MURRAY†& I. MINAMI†§ *Department of Oral Kinesiology, Academic Centre for Dentistry Amsterdam (ACTA), Research Institute MOVE, University of Amsterdam and VU University Amsterdam, Amsterdam, The Netherlands, †Faculty of Dentistry, Jaw Function and Orofacial Pain Research Unit, University of Sydney, Sydney, NSW, Australia, ‡Division of Gerodontology and Removable Prosthodontics, University of Geneva, Geneva, Switzerland and §Removable Partial Prosthodontics, Division of Oral Health Sciences, Graduate School, Tokyo Medical and Dental University, Tokyo, Japan

SUMMARY Masticatory efficiency in individuals with extensive tooth loss has been widely discussed. However, little is known about jaw movement smoothness during chewing and the effect of differences in food bolus location on movement smoothness and masticatory efficiency. The aim of this study was to determine whether experimental differences in food bolus location (anterior versus posterior) had an effect on masticatory efficiency and jaw movement smoothness. Jaw movement smoothness was evaluated by measuring jerk-cost (calculated from acceleration) with an accelerometer that was attached to the skin of the mentum of 10 asymptomatic subjects, and acceleration was recorded during chewing on two-colour chewing gum, which was used to assess masticatory efficiency. Chewing was performed under two conditions: posterior chewing (chewing on molars and premolars only) and anterior chewing (chewing on canine and first premolar teeth only). Jerk-cost and masticatory efficiency (calculated as the ratio of unmixed azure colour to the total area of gum, the unmixed fraction) were compared between anterior and posterior chewing with the Wilcoxon signed rank test (two-tailed). Subjects chewed significantly less efficiently during anterior chewing than during posterior chewing ($P=0.0051$). There was no significant difference in jerk-cost between anterior and posterior conditions in the opening phase ($P=0.25$), or closing phase ($P=0.42$). This is the first characterisation of the effect of food bolus location on jaw movement smoothness at the same time as recording masticatory efficiency. The data suggest that anterior chewing decreases masticatory efficiency, but does not influence jerk-cost.

KEYWORDS: jaw movement, mastication, accelerometer, jerk-cost, acceleration, chewing efficiency

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Introduction

The aim of mastication is to reduce food size to produce a homogeneous bolus appropriate to be swallowed (1). The restoration of masticatory function is an important aim in dentistry when patients present with extensive tooth loss. Some studies have shown that patients may compensate for posterior tooth loss by chewing longer (2), by swallowing larger food particles or by selecting a softer diet (3).

Masticatory function has been assessed objectively using clinical tests to obtain measures of masticatory efficiency or subjectively by means of questionnaires to obtain a measure of masticatory ability (4). Masticatory efficiency can be evaluated by studying the particle size distribution of foodstuffs after a given number of
chewing strokes and with the use of a sieve system (5–7). This sieving method has been specifically defined as ‘masticatory performance’ (5). Clear associations have been demonstrated between masticatory efficiency and dental state (8). Masticatory efficiency can also be assessed by measuring the mixing of a two-colour chewing gum (4, 9, 10) or a two-colour wax (11–13). The latter two methods are easy to perform (4, 12), and the masticatory efficiency assessed by these methods is highly correlated with the measures of masticatory efficiency derived from the sieving or particle size distribution method (13).

The number of occluding pairs of teeth has been shown to be closely correlated with masticatory efficiency, and individuals with < 20 teeth have a poorer masticatory performance than those with > 20 teeth. The values noted for number of chewing strokes, swallowing time and chewing time were smaller for those with a good masticatory performance, but the variation was not linear and not always significant (6). Changes in food type and thickness, Angle’s Class and trial repetition have been shown to have significant effects on some of the parameters of jaw movements during chewing (14). Further, it is well established that patients without molars have reduced ability to comminute food (1, 3, 15). However, epidemiological studies suggest that these individuals still retain sufficient chewing ability to maintain reasonable health (16, 17).

Masticatory efficiency in patients with extensive tooth loss has been discussed previously (7, 8); however, little is known about the effect of tooth loss on movement smoothness. Human movement smoothness has been described by mathematical models for limb (18, 19) and jaw movements (20). This study was carried out to provide some insight into the relation between jaw movement smoothness and masticatory efficiency. We chose to study the effect of changing the bolus location on jaw movement smoothness and masticatory efficiency. We propose that anterior chewing in an individual with a full complement of teeth would be associated with a lower masticatory efficiency, given that chewing on a smaller occlusal table as offered by the anterior teeth might be less efficient than chewing on the posterior teeth. Further, given that the food bolus is guided onto the occlusal table by tongue and cheek activation in opening and closing (21), subjects may not be able to use this tongue and cheek activation with anterior chewing in the same way as for posterior chewing. This may affect the skill with which the gum bolus is guided and moulded in relation to the occlusal table during chewing, and this may have an influence on masticatory efficiency (22). We, therefore, also proposed that anterior chewing might be associated with lower jaw movement smoothness, given that anterior chewing in these individuals would be less commonly performed in comparison with chewing movements involving the posterior teeth.

The aim of this study was to determine whether experimental differences in food bolus location (anterior versus posterior) had an effect on jaw movement smoothness and masticatory efficiency. The hypotheses to be tested were as follows: (i) anterior chewing is less efficient in comparison with posterior chewing and (ii) mandibular movement is less smooth during anterior chewing than during posterior chewing.

**Materials and methods**

**Subjects**

Approval from the ethics committee of the University of Sydney was obtained (protocol number 2479). Informed, signed consent was obtained from 10 volunteers (six men and four women, aged 23–35 years, mean ± s.d.: 30 ± 3.7 years). Inclusion criteria were as follows: Angle’s class I occlusion and complete permanent dentition except for the third molar teeth (28 teeth, 12 occluding premolar units). Exclusion criteria were as follows: history of temporomandibular muscle and joint disorders (TMJD) and severe periodontal disease, dental caries. Some of the procedures have been previously described (4, 23).

**Procedures**

Each subject was seated in an upright and relaxed position with his or her head unsupported and naturally oriented (20). The subjects were initially asked to chew, as normally as possible, 20 chewing strokes with commercially available two-colour gum (azure and white colour, 30 × 18 × 3 mm, Hubba-Bubba Tape Gums*) on the preferred chewing side posterior teeth (with the molars and premolars) (4).

*The Wrigley Company Ltd, Plymouth, Devon, UK.
One chewing stroke was defined as a single open and close chewing movement. Then the subjects chewed 20 strokes on the preferred chewing side anterior teeth (with the incisors and canine teeth), and this was performed with a new piece of two-colour gum. Chewing was commenced and stopped on instruction from the experimenter. The position of the gum in the anterior or posterior region was visually checked before starting chewing, during chewing (where it was possible to see) and immediately after completion of the chewing sequence (when the subject was asked to stop chewing and open the mouth for inspection for bolus location).

To randomise whether subjects chewed on the posterior teeth or the anterior teeth first, the subjects were divided randomly into two groups. The first group was instructed to chew first on the posterior teeth and then, with a separate piece of gum, on the anterior teeth; the second group performed the experiment in the reverse order. Each recording was performed over only one session to avoid changes in the subject’s skillfulness of chewing through repetition of the task too many times. The reliability of this procedure was confirmed in a previous study (23).

Measurement of masticatory efficiency

The gum was placed on the tongue, and the participant was asked to masticate the specimen for 20 chewing strokes, either with the anterior or with the posterior teeth. The gum was then retrieved from the oral cavity, placed in a transparent plastic bag and flattened with a plastic template to a 1-mm-thick wafer (Fig. 1). Both sides of the wafer were scanned with a flatbed scanner (Canon CanoscanLide 40†) at a resolution of 500 dots per inch (dpi). The resulting two images (front and back) were copied in a template of fixed size (2350 × 925 dpi, total of 2 173 750 pixels) and saved in photoshop format. The ‘magic wand tool’ at three different tolerances (4) and the ‘histogram function’ of Adobe Photoshop Elements 2.0‡ were used to count the total number of pixels of unmixed azure colour. Subsequently, the ratio of unmixed azure pixels to the total pixels of the original template was calculated [unmixed fraction (UF)] as an inverse measure of the masticatory efficiency (4).

Measurement of jerk-cost

Triaxial piezoelectric accelerometers (TPAs) (23, 24) with an output of 500 mV ms$^{-2}$ were chosen for their size (4·6 × 4·6 × 1·3 mm), low inertial mass (0·8 g) and broadband linearity (direct current to 5 kHz). The accelerometer was attached by means of a double-sided tape, pasted on the surface of medicine tape (Fixmull stretch§) attached to the skin of the jaw mentum of each subject. The accelerometer was positioned on the chin in such a way that the acceleration was recorded along three axes, thus enabling the following TPA output data: sagittal [Z, anterior and posterior (A–P) direction], vertical [Y, up and down (U–D) direction] and frontal [X, right and left (R–L) direction]. Three output channels from the TPA were amplified 100 times with a portable accelerometer pre-amplifier (custom made), were then digitised with 16-bit resolution at 1000 Hz sampling rate and were transferred to a laptop personal computer for software-based signal monitoring (LabDAQPro-CT¶).

To define the border of the opening and closing phases of the chewing stroke, a custom-made jaw-tracking device (23) was used to monitor vertical jaw displacement. This device consisted of a chin cap connected to lightweight headgear with an elastic band and incorporated a non-invasive sensor that measured the vertical location of the mandible relative to the jaw position at tooth contact.

Mathematical analysis software (Origin 8 Pro**) converted voltage data from the accelerometer into units of acceleration with the use of calibration data obtained from a vibration shaker system from a previous study (23). The acceleration data were then differentiated over time for each of the X-, Y- and Z-direction series. The three-dimensional jerk-cost (m$^{2}$ s$^{-5}$) data were then obtained from the following equations:

\[
\text{Jerk} - \text{cost} = \frac{1}{2} \int_{0}^{T} \left\{ \text{Jerk}_x^2(t) + \text{Jerk}_y^2(t) + \text{Jerk}_z^2(t) \right\} dt
\]

\[
\text{Jerk}(t) = \frac{d\{\text{acd}(t)\}}{dt}
\]

†CanoscanLide 40; Canon Inc., Tokyo, Japan.
‡Adobe Systems Inc., San Jose, CA, USA.
§BSN Medical GmbH, Hamburg, Germany.
¶Matsyama, Ehime, Japan.
**OriginLab, Northampton, MA, USA.

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For each subject, the mean jerk-cost value of five chewing strokes after the initial three strokes in the chewing sequence was used for analysis, in accordance with procedures described in previous studies (23, 24). The jerk-cost values were calculated for the following phases of each chewing stroke, and therefore, three jerk-cost values were derived: opening jerk-cost, closing jerk-cost and combined jerk-cost for opening + closing (24). As the duration of the masticatory stroke has been identified as an important measure of masticatory function, duration (s) was also calculated for these phases.

Statistics

The Wilcoxon signed rank test for paired comparisons were carried out to test for significant differences of the jerk-cost and the duration between the anterior and posterior teeth for the opening and closing phases and for the complete chewing stroke, with a significance level of $P < 0.05$. The masticatory efficiency was compared between anterior and posterior chewing with the non-parametric Wilcoxon signed rank test for paired samples. Non-parametric tests were selected because of the small sample size and because the jerk-cost data were not normally distributed. All the statistics were performed using STATA Statistical Software release 9.2††.

Results

Masticatory efficiency

There was a highly significant difference in masticatory efficiency between anterior (UF: median 0.091; interquartile range 0.048) and posterior (UF: median 0.023; interquartile range 0.023) chewing ($P = 0.0051$, Wilcoxon test). These data are shown in Table 1 for all subjects and are plotted in relation to previously published data (4) in Fig. 2. Inspection of the log-scale graph shows that 20 strokes of anterior chewing result in a masticatory efficiency that is equivalent to that achieved in about eight chewing strokes by the participants in the previous validation study (4), while 20 strokes of posterior chewing in this study (mean UF = 0.026) are equivalent to that achieved in about 22 strokes in the validation study (4) (difference from validation study, $P = 0.146$, Mann–Whitney).

Jerk-cost

Typical jerk-cost data are shown in Fig. 3 for two chewing strokes of anterior chewing (upper panel) and posterior chewing (lower panel) from one subject (#2). The vertical displacement of the mandible is shown by

![Fig. 1.](image)

To assess masticatory efficiency, a two-colour chewing gum (a) is masticated for 20 chewing strokes (b) and subsequently flattened to a 1-mm-thick wafer (c), which is then analysed opto-electronically.

<table>
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<th>Posterior</th>
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<td>6</td>
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</tr>
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<td>0.021</td>
</tr>
<tr>
<td>8</td>
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<td>9</td>
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<tr>
<td>10</td>
<td>0.115</td>
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<tr>
<td>IQR</td>
<td>0.048</td>
<td>0.023</td>
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s.d., standard deviation; IQR, interquartile range.

††Stata Corporation, College Station, TX, USA.
were no statistically significant differences for jerk-cost in the opening phase between posterior (jerk-cost: median 4167.8; interquartile range 3473.2 m² s⁻³) chewing and anterior (jerk-cost: median 5214.0; interquartile range 9301.9 m² s⁻³) chewing ($P = 0.25$, Wilcoxon test) or in the closing phase between posterior (jerk-cost: median 2682.6; interquartile range 1659.3 m² s⁻³) and anterior (jerk-cost: median 2773.3; interquartile range 3886.0 m² s⁻³) chewing locations ($P = 0.42$, Wilcoxon test) (Table 2). There was no significant difference in jerk-cost for the complete chewing stroke between posterior (jerk-cost: median 6188.5; interquartile range 5066.4 m² s⁻³) and anterior (jerk-cost: median 7987.2; interquartile range 11 400.9 m² s⁻³) chewing ($P = 0.42$, Wilcoxon test).

There were no statistically significant differences for the duration values in the opening phase between posterior (duration: median 0.35; interquartile range 0.24 s) chewing and anterior (duration: median 0.34; interquartile range 0.13 s) chewing ($P = 0.14$, Wilcoxon test) or in the closing phase between posterior (duration: median 0.44; interquartile range 0.13 s) and anterior (duration: median 0.44; interquartile range 0.22 s) chewing locations ($P = 0.20$, Wilcoxon test). There was no significant difference for the complete chewing stroke between posterior (duration: median 0.75; interquartile range 0.33 s) and anterior (duration: median 0.75; interquartile range 0.24 s) chewing ($P = 0.96$, Wilcoxon test).

**Discussion**

The findings of this study show that jerk-cost and chewing cycle duration, in the opening or closing phases of chewing, were not significantly different between posterior and anterior chewing. However, there was a significantly greater masticatory efficiency during posterior chewing in comparison with that of anterior chewing.

**Masticatory efficiency**

Chewing was significantly less efficient when the location of the gum chewing was transferred from the posterior teeth to the anterior teeth. These findings support the first hypothesis of the study that anterior chewing is less efficient in comparison with posterior chewing. The data are also consistent with previous findings, which demonstrated that the loss of posterior chewing...
occluding units results in reduced masticatory efficiency (1, 3, 8). The reduction in masticatory efficiency may relate to the smaller occlusal table used with anterior chewing than posterior chewing as well as the possibility of a lower skillfulness of subjects with anterior in comparison with posterior chewing, given that fully dentate subjects principally chew on their posterior teeth and would be less likely to chew on their anterior teeth.

However, it should be pointed out that the subjects in this study were fully dentate, and thus, the anterior chewing would have been a conscious act that is likely not to have fully reproduced the chewing that would occur in an individual with a reduced dentition. Despite the loss of posterior periodontal receptors and teeth, neuroplastic changes (25) associated with the loss of posterior teeth might well result in a higher masticatory efficiency than could be demonstrated in this study, given that these individuals would have had a long period of learning associated with the gradual reduction in dental state. These adaptive changes might compensate for the posterior tooth loss by chewing longer (2), by swallowing larger food particles or by selecting a softer diet (3). The subjects of this study were simply asked to chew on the anterior teeth on the preferred chewing side, and this would have required an immediate change in the neural control of the chewing stroke to achieve this.

Two-colour gum as a measure of masticatory efficiency
The gold standard for measuring masticatory efficiency remains the sieving method (7). In this method, test food is chewed for a given number of strokes; the food is then retrieved, dried and subsequently the distribution of particle sizes are analysed with a sieve system and the Rosin–Rammler formula (26). Although this food comminution test most directly describes masticatory efficiency, it exhibits some limitations. Test foods are often natural food like nuts or coffee beans (27), which can be difficult to standardise. To overcome this problem, the ‘Optosil’ test was described, which is a sieving method that employs blocks of silicone as the test food. A disadvantage of the sieving method is that it is time consuming, and therefore, in this study, a previously described two-colour mixing ability test was employed to evaluate masticatory efficiency (4) and is based on the experiments of Liedberg (28), Prinz (29) and Anastassiadou (30). The method evaluates masticatory efficiency through the individual colour mixing ability and sweetener extraction using a specimen that is easy to standardise.

Jerk-cost measurement with an accelerometer on the chin
The derivation of jerk-cost from an accelerometer has a number of advantages over deriving jerk-cost from the

Table 2. Jerk-cost values for anterior chewing and posterior chewing for each of the opening phase, the closing phase and full stroke (m/s²)
output of conventional jaw-tracking systems. An accelerometer allows direct measurement of acceleration, and therefore, the jerk can be obtained from the one time derivative. The output from an accelerometer can be sampled at higher rates, for example, 1000 Hz, than from conventional jaw-tracking systems, and this will allow the recording of high-frequency jaw accelerations (23, 24, 31). Attachment of the accelerometer directly to the chin may be a less valid indicator of mandibular movement than if the accelerometer had been attached to the teeth because the skin will act as a low-pass filter attenuating high-frequency accelerations. However, our previous study (24) reported comparable jerk-cost values to those reported here, and these values were calculated from an accelerometer that was attached rigidly directly to the teeth via the lower clutch of the jaw-tracking system used in that study. Another issue to consider in this study is that the elastic band attaching the chin cap to the head gear of the jaw movement recording device could also have influenced mandibular movement. Nonetheless, we believe this method of attaching the accelerometer to the skin of the chin does provide a valid measure of acceleration and therefore jerk-cost in this experiment.

Jerk-cost and food bolus location

The jerk-cost data did not demonstrate statistically significant differences following a change in the chewing bolus location from the posterior teeth to the anterior teeth, although subjects #2, 3, 6, 7, 8, 9 and 10 demonstrated greater smoothness (i.e. lower jerk-costs) during the opening phase of posterior gum chewing than for anterior chewing, and subjects #1, 2, 3, 6, 7, 9 and 10 demonstrated greater smoothness during the closing phase of posterior gum chewing than for anterior chewing.

The jerk-cost was graphically represented as an area in the time differential of jerk-costs graph (Fig. 3). The peak areas represent sudden changes of movement which occur early in the opening phase as the teeth move apart and as the gum separates from the teeth, and in the closing phase before the teeth come into contact with the gum. These waveforms were in general similar in shape between anterior and posterior chewing, but exhibited considerable variability. This variability in jerk-cost values across the entire chewing cycle could possibly mask differences of jerk-cost between anterior and posterior chewing. Another factor is the possible influence of the devices used in this study. The accelerometer was attached to the skin of the chin, and the low-pass filtering effects of the skin could influence its sensitivity. The target frames of the jaw-tracking device were attached to the teeth, and the attachment could have influenced the kinematics of jaw movement. It is possible that any such effects might mask any potential differences between anterior and posterior chewing.

The jerk-cost value in this study was much larger than in the previous study, for example, the mean values of jerk-cost for the analysis period were \(11772 \times 10^{-5} \text{m}^2 \text{s}^{-5}\) in this study, but \(3502 \times 10^{-5} \text{m}^2 \text{s}^{-5}\) in the previous study. The following differences between the present and our previous study (23) may explain these differing findings. First, the texture, size and/or viscosity of the gum used in this study (namely, a two-colour gum) possibly may be different from that of the gum (namely, a peppermint-flavoured normal chewing gum) used in our previous study. A second reason could be that the magnitude of masticatory force could be greater in this study than in the previous study because subjects may have been motivated to achieve good results, given that they understood the aim of the study. Jerk-cost, an inverse measure of movement smoothness, may therefore also have been affected by these motivational aspects. Further investigation is encouraged to assess the impact of the viscosity of the gum on jerk-cost during the empty chewing.

Limitations of study

Limitations regarding the jaw movement system have been discussed previously. The two-colour mixing ability test is an indirect measure of masticatory efficiency. However, it does correlate with the sieving method (gold standard) (32) and demonstrates an ability to detect changes in prosthetic rehabilitation (11), different occlusal conditions (33) or changes in functional status of the orofacial system (10).

Conclusion

This pilot study has demonstrated a statistically significant difference in masticatory efficiency between anterior and posterior chewing, without a change of movement smoothness. This study could provide information on the adaptability of the jaw motor system to
variations in posterior tooth loss. These results encourage the further study of the effects of the bolus location on the jerk-cost comparing to that of empty chewing.

Acknowledgments

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Correspondence: Dr Ichiro Minami, Jaw Function and Orofacial Pain Research Unit, Faculty of Dentistry, University of Sydney, Professorial Unit, Level 3, Westmead Hospital Centre for Oral Health, Westmead, NSW 2145, Australia. E-mail: minami.rpro@tmd.ac.jp