Clinical Practice

# Modulation of the masticatory path at the mandibular first molar throughout the masticatory sequence of a hard gummy jelly in normal occlusion

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Objective: In this study, the authors investigated the modulation of the masticatory path at the mandibular first molar during natural chewing of a hard gummy jelly in adults with normal occlusion.

Methods: The unilateral mastication sequence was divided into three stages, and the masticatory path of the mandibular first molar on the working side was analyzed at 2.0, 3.0, 4.0 and 5.0 mm vertical slice levels below the intercuspation in the frontal and sagittal views.

Results: In the frontal view, the closing and opening angles and cycle width of the final stage at 3.0, 4.0, and 5.0 mm slice levels were smaller and narrower than those of the initial stage, although those at the 2.0 mm slice level were little changed.

Discussion: Masticatory paths at slice levels greater than 3.0 mm were evidently modulated to adapt to the changing properties of the food, and those at the 2.0 mm slice level remained stable throughout the masticatory sequence.

**Keywords:** Jaw movement; Masticatory sequence; Masticatory path

**Introduction**

Mastication is a physiological process controlled by the central nervous system[1-3] and modulated by extensive sensory input from the oral cavity.[4-6] Sensory feedback from different types of peripheral receptors, such as the periodontal receptors and the muscle spindles of elevator muscles, allows the motor program to adapt continuously to the changing properties of the food throughout the masticatory sequence.[7-14] To cut and grind the food precisely, these adaptations occur during mastication, whereby softening of the food, particle size reduction, and lubrication progressively transform the food into a bolus suitable for swallowing.

In previous studies, it has been shown that the mechanical properties of foods are significantly correlated with masticatory jaw movement,[11-13,15-17] whereby hard foods are chewed with wider jaw movements than soft foods.[18,19] In addition, investigations into the role of occlusal guidance have reported an approximate occlusal glide length of less than 2.0 mm.[20-22] A masticatory path with no occlusal contact is not directly affected by occlusal guidance, but rather by muscles, joint ligaments, and possibly by the inclination of the occlusal plane and other factors.[23-25] Therefore, the masticatory path during the occlusal phase can be categorized into two phases: a stable masticatory path affected by individual morphological factors, and a varied masticatory path adapted to ongoing textural changes in the food bolus throughout the masticatory sequence. However, how the relationship between the stable and varied masticatory paths changes throughout the masticatory sequence is poorly understood, and no previous study has investigated masticatory path modulations during natural chewing in the frontal and sagittal views at several vertical slice levels. The movement of the lower central incisor point differs from that of the mandibular first molar during chewing,[26,27] but direct examination of the movement of the first molar on the working side throughout the masticatory sequence would be beneficial, as this is the tooth that actually crushes and grinds food.

The aim of this study was to investigate the masticatory path of the mandibular first molar at several vertical slice levels in the frontal and sagittal views throughout mastication of a hard gummy jelly. The authors hypothesized that it may be possible to reveal the neuromuscular aspects of the masticatory system that modify the masticatory path to adapt to changes in the properties of food that occur throughout the masticatory sequence.

## Materials and Methods

### *Subjects*

Seventeen healthy subjects (14 men, 3 women; mean age 21.6 years; range 19–24 years) with normal occlusion and function were selected from Kagoshima University Faculty of Dentistry students. The inclusion criteria were as follows: complete Angle Class I canine and molar relationship, normal overjet and overbite, permanent dentition fully emerged (excluding third molars), little crowding and rigid intercuspation, no current or recent dental or orthodontic treatment, and no clinical signs or symptoms of temporomandibular disorders (TMD) according to a clinical examination and responses to a questionnaire based on the Research Diagnostic Criteria for TMD Axis I.[28] The study was approved by the Ethics Committee of Kagoshima University Hospital (application number #25-116). All subjects provided written informed consent after receiving a full explanation of the study goals and structure.

*Test foodstuff*

A standardized hard gummy jelly (5 g) was used as the test foodstuff (Meiji Seika Kaisha Ltd. Confectionery R&D Labs, Saitama, Japan). It had a truncated cone shape (height = 11 mm, top diameter = 12 mm, base diameter = 22 mm) and a coherent bolus.[15,17]

*Recording and analysis of jaw movement*

A jaw tracking system with six degrees of freedom was used to record mandibular movement, as previously described.[15,17,29-33] The system consisted of a head frame, a face bow, a pointer, light-emitting diodes (LEDs), charge-coupled device (CCD) cameras, an amplifier, and a personal computer (GNATHO-HEXAGRAPH II®; GC International Co. Tokyo, Japan). The head frame and face bow, each of which had three LEDs, were attached securely to the head and the lower anterior teeth, respectively, via a dental clutch. The dental clutch was bent to ensure minimal inhibition of movement of the mandible and lips. A stand supporting two vertically installed CCD cameras was placed 1.2 meters in front of the subject. Movements of the lower central incisor points and mesio-buccal cusps of the mandibular first molars were recorded on the right and left using a pointer with two LEDs. The accuracy of the recording equipment has been tested previously by Tokiwa *et al.*,[34] and the mean measurement error of the system is 0.12 mm.

*Experimental procedure*

Each subject was seated on a chair in a comfortable upright position, with his or her head naturally oriented. During recording, they were asked to stare fixedly at a red point on the CCD camera. To determine the preferred chewing side (PCS), the subject was instructed to chew a piece of gum. During 30 seconds of free chewing, the number of strokes on the right and left were counted. This process was repeated three times, and the dominant side was defined as the PCS. After the PCS had been determined, a gummy jelly was placed on the tongue of each subject, with the maximum intercuspation. This position was used as the point of central occlusion for each measurement. Each subject performed deliberate unilateral chewing of the gummy jelly on the PCS twice. The complete masticatory sequence was recorded, from the first cycle to the final swallowing action. Because the first session was an exercise in which the subject first experienced chewing under experimental conditions and perception of the properties of the test food, the second session was used for analysis of masticatory jaw movement.

*Data analysis*

The jaw movement throughout the unilateral masticatory sequence of a gummy jelly was analyzed using customized software (University of Kagoshima, Kagoshima, Japan). Cycles were excluded if they had at least one of the following characteristics: (1) minimum opening smaller than 4 mm; (2) duration shorter than 300 milliseconds; or (3) vertical opening smaller than 3 mm.[19] Each complete masticatory sequence was divided into three equal sections based on the number of chewing cycles; the initial, middle, and final stages. The authors selected the 10 cycles from beginning of each stage, and analyzed the mean value for 10 representative cycles at each stage. The chewing cycle variables in the frontal and sagittal views are shown in Figure 1. The following variables were calculated: maximum extrusion in inferior, chewing side, non-chewing side, anterior and posterior direction, minimum gap, maximum cycle width, and cycle duration. Figure 2 shows the masticatory path variables at 2.0, 3.0, 4.0 and 5.0 mm vertical slice levels in the frontal and sagittal views. The closing and opening angles were determined at slice levels from 2.0–5.0 mm below the intercuspation. Cycle widths at 2.0–5.0 mm slice levels were defined as the lateral distance between the closing and opening paths in the frontal view, and the anteroposterior distance between the closing and opening paths in the sagittal view.

*Statistical analyses*

All data were analyzed with statistical software (SPSS® version 20 for Windows, SPSS Japan Inc., Tokyo, Japan). The significance of any differences between the stages was evaluated by analysis of variance (ANOVA). When significant effects were identified, a multiple comparison post-hoc test (Bonferroni-Dunn) was performed. All statistical analyses were performed with significance set at the 0.05 probability level. In *a priori* power analysis, the authors performed a sample size calculation[35] using data derived from a pilot study performed with seven normal subjects. The statistical significance of the closing angle at the 5.0 mm slice level in the frontal view among each stage was evaluated by ANOVA ($P < 0.05$). In a multiple comparison post-hoc test, the variable means (with standard deviations; SDs) were 35.4 (SD 5.5) in the initial stage and 31.0 (SD 5.6) in the final stage. The correlation between groups was 0.5. Assuming a significance level of $P < 0.05$, with a power of 0.8, and an effect size of 0.79, the number of subjects with normal occlusion required was 15.

**Results**

The mean number of whole chewing cycles was 73.8 (SD 31.9) and the mean duration of one complete masticatory sequence was 59.6 seconds (SD 25.3). The mean number of chewing cycles from each stage in the frontal and sagittal views is shown in Figure 3. Comparisons of chewing cycle variables are shown in Table 1. ANOVA of the maximum excursions in inferior, chewing side, non-chewing side, and posterior direction, minimum gap, and maximum cycle width revealed a significant effect of stage ($P < 0.05$), although there were no significant differences in anterior excursion or cycle duration between the stages. The inferior excursion was significantly larger in the initial and middle stages, compared with the final stage ($P < 0.05$). Non-chewing side excursion in the initial stage was significantly larger than in the middle and final stages ($P < 0.05$). The chewing side and posterior excursions in the initial stage were significantly larger than in the final stage ($P < 0.05$). The minimum gap and maximum cycle width showed significant and progressive reductions from the initial to the middle and final stages ($P < 0.05$).

Table 2 shows the results of masticatory path variables at 2.0–5.0 mm slice levels in the frontal view. ANOVA of the closing and opening angles and of the cycle widths at 3.0, 4.0, and 5.0 mm slice levels revealed a significant effect of stage ($P < 0.05$); however, no such effect was observed at the 2.0 mm slice level. Closing angles at the 3.0 mm slice level in the final stage were significantly smaller than those in the initial stage ($P < 0.05$). Closing angles at the 4.0 mm slice level in the middle and final stages were significantly smaller than those in the initial stage ($P < 0.05$). Significant reductions in the closing angle at the 5.0 mm slice level were observed in each stage ($P < 0.05$). In addition, the opening angles and the cycle widths at 3.0, 4.0, and 5.0 mm slice levels were significantly reduced in each stage ($P < 0.05$).

Table 3 shows the results of masticatory path variables at 2.0–5.0 mm slice levels in the sagittal view. The ANOVA of the closing and opening angles and cycle width in the sagittal view did not reveal any significant effect of stage, except in the opening angle at the 5.0 mm slice level ($P < 0.05$). Only the opening angle at the 5.0 mm slice level in the final stage was significantly smaller than that in the initial stage ($P < 0.05$).

**Discussion**

It is important that any test foodstuff selected for the study of mastication has a homogeneous structure, a reproducible texture, a constant shape and size, and the ability to exhibit a complete hardness scale value.[7] The test foodstuff used in this study not only satisfied the above criteria, but could also induce a natural chewing motion. Another property of the gummy jelly used was that it has been classified as belonging to the hardest food group, according to a study that ranked conventional everyday foods based on 10 levels of hardness.[36] When chewing a food of this hardness, in the initial stage there is not much occlusal contact between the upper and lower teeth. In this study, the minimum gap between the upper and lower molars decreased from 0.8 mm in the initial stage to 0.3 mm in the middle stage and 0.1 mm in the final stage, indicating that the gummy jelly softened and showed a reduction in particle size over time. The statistical power of a study should be as high as possible, to ensure the reliability of the results, and this sample size calculation revealed that a sample of 15 subjects was sufficient for achieving 80% power. Because the observations of 17 subjects were analyzed in this study, the statistical power of the study was sufficiently high to ensure reliability.

The authors found that during a masticatory sequence, the inferior excursion and maximum cycle width at the mandibular first molar tend to decline gradually, which is consistent with previous results reported for incisors.[11-13, 15-17] These chewing cycles can be interpreted as an adaptation to the softening of the food, and to the reduction in particle size that occurs during the entire masticatory sequence. Extensive oral sensory information on the changes in the properties of the food, and its location, is provided by the tongue and oral mucosa,[37] muscle spindles,[38] and periodontal pressoreceptors.[4-6] The previous study suggested that humans chew hard foods in such a way that the mandibular teeth that come into contact with the food open to a height equivalent to that of the food bolus, and that changes in the jaw movement are minimized to ensure efficient mastication.[15] It can be assumed that the chewing pattern at the first mandibular molar with rhythmical and smooth movements was continuously and immediately modified by peripheral information, which related to the progressively changing mechanical properties of the food during a masticatory sequence.

There are no clear indications as to whether the pathways of the mandibular first molars observed throughout the masticatory sequence are identical at several slice levels in the frontal and sagittal views. Occlusal morphology is closely related to jaw movement during the last millimeters of the closing phase.[39,40] However, the closing angle has been shown to be dependent only on the hardness of the bolus, whereby it is smaller with soft chewing-gum or gummy foods than it is with harder foods.[18,19] In the present study, the closing and opening angles at the 2.0 mm slice level in the frontal view were stable throughout the masticatory sequence, which is comparable to the former reports.[39,40] Conversely, these angles at 3.0, 4.0, and 5.0 mm slice levels in the frontal view gradually decreased with the progression of mastication, which is consistent with the latter reports.[18,19] Considering that the length of occlusal guidance has been reported to be approximately 0.79–1.59 mm at the central incisor,[20,41] the masticatory path of the mandibular first molar at the 2.0 mm slice level below the intercuspation was presumed to be almost without occlusal contact. The preferable position to break down the food forcefully in this phase may be precisely controlled by a neuromuscular system of mastication throughout the masticatory sequence. Furthermore, the closing pathways that do not involve occlusal contact are reportedly affected by muscles, joint ligaments, and possibly by the inclination of the occlusal plane.[23-25] These individual morphological factors might also be associated with the stability of the masticatory path of the mandibular first molars at the 2.0 mm slice level, regardless of the hardness and size of the food particle.

In the present study, the masticatory paths of the mandibular first molar at slice levels greater than 3.0 mm were characterized by wide lateral pathways at the initial stage, but these were replaced by narrow vertical pathways at the final stage. These changes between the initial, middle, and final stages at slice levels greater than 3.0 mm are thought to be modulated by sensory input relating to the changing physical properties of the food. Bite force is a compressive force that acts between a pair of opposing occlusal contact areas.[42] Multiple occlusal contacts sustain loads from jaw closing muscle contraction directly, or indirectly through food with upper and lower tooth contact.[43] Broader contact areas provide better occlusal support, and allow the elevator muscles to act more forcefully during chewing. Previous reports have indicated that the occlusal load is initially transferred in a direction perpendicular to the cuspal inclines of the posterior teeth,[42,44] suggesting that the principal loading positions of the mandibular posterior teeth are generally on the lingual inclines of the buccal cusps. When chewing a hard and large food, such as the jelly that was hard and gummy at the initial stage of chewing in this study, it is necessary to overcome the resistance of the food with high muscle activity between the inner inclines of the cusps of the posterior teeth. Wider lateral masticatory pathways may contribute to catching food with broad occlusal contact, which facilitates forceful and stable mastication.

In contrast to the modulations of the masticatory paths observed throughout the masticatory sequence in the frontal view, the masticatory paths observed in the sagittal view changed little, and remained steady at all slice levels. A previous study demonstrated that bite force was inclined slightly anteriorly from a perpendicular direction to the mandibular occlusal plane.[42] This direction on the occlusal surface of the mandibular dentition is similar to that of the natural opening-closing path. It has also been suggested that the distal inclines of the buccal cusps of the mandibular molars bear the principal occlusal load in normal occlusion.[44] The findings of this study suggest that modulation of the anteroposterior movement at the first molar is not generally necessary to adapt to the changing properties of food throughout the masticatory sequence.

As the limitation of this study, the hardness and the size of the food, as well as numerous other factors such as rheological characteristics, taste, flavor, and the previous experience of the food, modulate masticatory jaw movement.[45] Further, the oral sensory perception of food texture is dynamic and occurs during all stages of oral processing, and this varies among individuals. These factors may have influenced the individual physiological adaptations to the food texture in this study. However, the results of this study demonstrated modulation of the masticatory path from intraoral sensory feedback to ongoing textural changes in the food bolus throughout the masticatory sequence. These data provide the normal masticatory adaptations to the model food during natural chewing, and this can be a useful initial diagnostic test for impaired masticatory function in the clinical environment.

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**References**


1. Dellow PG, Lund JP. Evidence for central timing of rhythmical mastication. J Physiol. 1971;215(1):1-13.
2. Nozaki S, Iriki A, Nakamura Y. Localization of central rhythm generator involved in cortically induced rhythmical masticatory jaw-opening movement in the guinea pig. J Neurophysiol. 1986;55(4):806-25.
3. Lund JP, Enomoto S. The generation of mastication by the mammalian central nervous system. In: H. Cohen H, Rossignol S, Grillner S, editors. Neural Control of Rhythmic Movements. New York: Wiley; 1988. p.41-71.
4. Lavigne G, Kim JS, Valiquette C, Lund JP. Evidence that periodontal pressoreceptors provide positive feedback to jaw closing muscles during mastication. J Neurophysiol. 1987;58(2):342-58.
5. Morimoto T, Inoue T, Masuda Y, Nagashima T. Sensory components facilitating jaw-closing muscle activities in the rabbit. Exp Brain Res. 1989;76(2):424-40.
6. Ottenhoff FA, van der Bilt A, van der Glas HW, Bosman F. Peripherally induced and anticipating elevator muscle activity during simulated chewing in humans. J Neurophysiol. 1992;67(1):75-83.
7. Woda A, Foster K, Mishellany A, Peyron MA. Adaptation of healthy mastication to factors pertaining to the individual or to the food. Physiol Behav. 2006;89(1):28-35.
8. Thexton AJ, Hiiemae KM, Crompton AW. Food consistency and bite size as regulators of jaw movement during feeding in the cat. J Neurophysiol. 1980;44(3):456-74.
9. Schwartz G, Enomoto S, Valiquette C, Lund JP. Mastication in the rabbit: a description of movement

and muscle activity. J Neurophysiol. 1989;62(1):273-87.

10. Lund JP. Mastication and its control by the brain stem. Crit Rev Oral Biol Med. 1991;2(1):33-64.
11. Peyron MA, Maskawi K, Woda A, Tanguay R, Lund JP. Effect of food texture and sample thickness on mandibular movement and hardness assessment during biting in man. J Dent Res. 1997;76(3):789-95.
12. Peyron MA, Lassauzay C, Woda A. Effects of increased hardness on jaw movement and muscle activity during chewing of visco-elastic model foods. Exp Brain Res. 2002;142(1):41-51.
13. Lassauzay C, Peyron MA, Albuisson E, Dransfield E, Woda A. Variability of the masticatory process during chewing of elastic model foods. Eur J Oral Sci. 2000;108(6):484-92.
14. Prinz JF, Lucas PW. An optimization model for mastication and swallowing in mammals. Proc Biol Sci. 1997;264(1389):1715-21.
15. Miyawaki S, Ohkochi N, Kawakami T, Sugimura M. Effect of food size on the movement of the mandibular first molars and condyles during deliberate unilateral mastication in humans. J Dent Res. 2000;79(7):1525-31.
16. Foster KD, Woda A, Peyron MA. Effect of texture of plastic and elastic model foods on the parameters of mastication. J Neurophysiol. 2006;95(6):3469-79.
17. Miyawaki S, Tanimoto Y, Kawakami T, Sugimura M, Takano-Yamamoto T. Motion of the human mandibular condyle during mastication. J Dent Res. 2001;80(2):437-42.
18. Takada K, Miyawaki S, Tatsuta M. The effects of food consistency on jaw movement and posterior temporalis and inferior orbicularis oris muscle activities during chewing in children. Arch Oral Biol.

1994;39(9):793-805.

19. Piancino MG, Bracco P, Vallelonga 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(6):931-7.

20. Hayasaki H, Sawami T, Saitoh I, Nakata S, Yamasaki Y, Nakata M. Length of the occlusal glide at the lower incisal point during chewing. J Oral Rehabil. 2002;29(11):1120-5.

21. Rilo B, Fernandez J, Da Silva L, Martinez Insua A, Santana U. Frontal-plane lateral border movements and chewing cycle characteristics. J Oral Rehabil. 2001;28(10):930-6.

22. Neill DJ, Howell PG. Computerized kinesiography in the study of mastication in dentate subjects. J Prosthet Dent. 1986;55(5):629-38.

23. Ogawa T, Koyano K, Suetsugu T. The relationship between inclination of the occlusal plane and jaw closing path. J Prosthet Dent. 1996;76(6):576-80.

24. Ogawa T, Koyano K, Suetsugu T. Correlation between inclination of occlusal plane and masticatory movement. J Dent. 1998;26(2):105-12.

25. Ogawa T, Koyano K, Umemoto G. Inclination of the occlusal plane and occlusal guidance as contributing factors in mastication. J Dent. 1998;26(8):641-7.

26. Gibbs CH, Lundeen HC, Mahan PE, Fujimoto J. Chewing movements in relation to border movements at the first molar. J Prosthet Dent. 1981;46(3):308-22.

27. Gibbs CH, Lundeen HC. Jaw movements and forces during chewing and swallowing, and their clinical significance, In: Lundeen HC, Gibbs CH, editors. Advances in occlusion. 1st ed. Boston:

John Wright-PSG, Inc.; 1982. p.2-32.

28. Dworkin SF, LeResche L. Research diagnostic criteria for temporomandibular disorders: review, criteria, examinations and specifications, critique. J Craniomandib Disord. 1992;6(4):301-55.
29. Miyawaki S, Tanimoto Y, Araki Y, Katayama A, Kuboki T, Takano-Yamamoto T. Movement of the lateral and medial poles of the working condyle during mastication in patients with unilateral posterior crossbite. Am J Orthod Dentofacial Orthop. 2004;126(5):549-54.
30. Miyawaki S, Araki Y, Tanimoto Y, Katayama A, Fujii A, Imai M, *et al.* Occlusal force and condylar motion in patients with anterior open bite. J Dent Res. 2005;84(2):133-7.
31. Ohmure H, Miyawaki S, Nagata J, Ikeda K, Yamasaki K, Al-Kalaly A. Influence of forward head posture on condylar position. J Oral Rehabil. 2008;35(11):795-800.
32. Tomonari H, Kubota T, Yagi T, Kuninori T, Kitashima F, Uehara S, *et al.* Posterior scissors-bite: masticatory jaw movement and muscle activity. J Oral Rehabil. 2014;41(4):257-65.
33. Kuninori T, Tomonari H, Uehara S, Kitashima F, Yagi T, Miyawaki S. Influence of maximum bite force on jaw movement during gummy jelly mastication. J Oral Rehabil. 2014;41(5):338-45.
34. Tokiwa H, Miura F, Kuwahara Y, Wakimoto Y, Tsuruta M. Development of a new analyzing system for stomatognathic functions. J Jpn Soc Stomatognath Funct. 1996;3(1):11-24. [Article in Japanese]
35. Faul F, Erdfelder E, Lang AG, Buchner A. G*Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. Behav Res Methods. 2007;39(2):175-91.
36. Yanagisawa Y, Tamura A, Teramoto Y, Akasaka M. A classification of foods by the amount of

masticatory action involved. Shoni Shikagaku Zasshi. 1989;27(1):74-84. [Article in Japanese]

37. Appenteng K, Lund JP, Séguin JJ. Intraoral mechanoreceptor activity during jaw movement in the anesthetized rabbit. J Neurophysiol. 1982;48(1):27-37.

38. Goodwin GM, Luschei ES. Effects of destroying spindle afferents from jaw muscles on mastication in monkeys. J Neurophysiol. 1974;37(5):967-81.

39. Woda A, Vigneron P, Kay D. Nonfunctional and functional occlusal contacts: a review of the literature. J Prosthet Dent. 1979;42(3):335-41.

40. Wood WW, Gelfant H, Hannam AG. Effect of occlusal reconstruction on the reproducibility of chewing movements. J Prosthet Dent. 1981;46(2):181-4.

41. Rilo B, Fernández-Formoso N, Mora MJ, Cadarso-Suárez C, Santana U. Distance of the contact glide in the closing masticatory stroke during mastication of three types of food. J Oral Rehabil. 2009;36(8):571-6.

42. Hattori Y, Satoh C, Kunieda T, Endoh R, Hisamatsu H, Watanabe M. Bite forces and their resultants during forceful intercuspal clenching in humans. J Biomech. 2009;42(10):1533-8.

43. Van der Bilt. Assessment of mastication with implications for oral rehabilitation: a review. J Oral Rehabil. 2011;38(10):754-80.

44. Wang MQ, Zhang M, Zhang JH. Photoelastic study of the effects of occlusal surface morphology on tooth apical stress from vertical bite forces. J Contemp Dent Pract. 2004;5(1):74-93.

45. Foster KD, Grigor JM, Cheong JN, Yoo MJ, Bronlund JE, Morgenstern MP. The role of oral processing in dynamic sensory perception. J Food Sci. 2011 Mar;76(2):R49-61.

Table 1. Comparison of chewing cycle variables (mean ± SD) during mastication of a hard gummy jelly between stages. (n=17)

| Chewing cycle variables | Initial stage | Middle stage | Final stage | Statistical significance (P-value) | | |
|---|---|---|---|---|---|---|
| | | | | Initial vs. Middle | Middle vs. Final | Initial vs. Final |
| Maximum excursion (mm) | | | | | | |
| Inferior | 13.7 ± 3.1 | 12.9 ± 3.0 | 11.7 ± 2.9 | - | 0.013 | 0.001 |
| Chewing side | 4.6 ± 1.3 | 4.4 ± 1.2 | 4.1 ± 1.3 | - | - | 0.008 |
| Non-chewing side | 1.9 ± 1.4 | 1.1 ± 0.9 | 0.9 ± 0.9 | 0.015 | - | 0.009 |
| Anterior | 0.4 ± 0.8 | 0.5 ± 0.4 | 0.4 ± 0.4 | - | - | - |
| Posterior | 6.4 ± 2.5 | 5.9 ± 2.2 | 5.3 ± 1.7 | - | - | 0.031 |
| Minimum gap (mm) | 0.8 ± 0.5 | 0.3 ± 0.3 | 0.1 ± 0.2 | <0.0001 | 0.005 | <0.0001 |
| Maximum cycle width (mm) | 6.6 ± 1.7 | 5.5 ± 1.5 | 5.0 ± 1.5 | 0.001 | 0.014 | <0.0001 |
| Cycle duration (s) | 0.80 ± 0.27 | 0.75 ± 0.21 | 0.77 ± 0.2 | - | - | - |

P-value: post-hoc test (Bonferroni-Dunn)

- : Not significant

Table 2. Comparison of the masticatory path variables (mean ± SD) in the frontal view at the 2.0, 3.0, 4.0 and 5.0 mm slice levels during mastication between stages. (n=17)

| Masticatory path variables (Slice level) | Initial stage | Middle stage | Final stage | Statistical significance (P-value) | | |
|---|---|---|---|---|---|---|
| | | | | Initial vs. Middle | Middle vs. Final | Initial vs. Final |
| Closing angle (°) | | | | | | |
| 2.0 mm | 42.4 ± 11.5 | 41.2 ± 9.2 | 40.7 ± 9.6 | - | - | - |
| 3.0 mm | 42.0 ± 9.5 | 39.7 ± 8.0 | 36.8 ± 7.2 | - | - | 0.013 |
| 4.0 mm | 40.8 ± 7.9 | 36.7 ± 6.8 | 35.3 ± 6.5 | 0.016 | - | 0.002 |
| 5.0 mm | 37.9 ± 6.8 | 34.4 ± 6.6 | 32.3 ± 6.5 | 0.006 | 0.024 | <0.0001 |
| Opening angle (°) | | | | | | |
| 2.0 mm | 21.7 ± 19.3 | 17.7 ± 23.0 | 13.8 ± 24.0 | - | - | - |
| 3.0 mm | 21.6 ± 18.3 | 13.8 ± 19.4 | 9.4 ± 19.6 | 0.025 | 0.017 | 0.003 |
| 4.0 mm | 19.3 ± 17.1 | 9.9 ± 17.2 | 6.1 ± 17.6 | 0.004 | 0.022 | 0.001 |
| 5.0 mm | 16.7 ± 15.5 | 7.5 ± 15.2 | 1.9 ± 15.5 | 0.003 | 0.013 | 0.001 |
| Cycle width (mm) | | | | | | |
| 2.0 mm | 2.8 ± 1.3 | 2.6 ± 1.3 | 2.4 ± 1.4 | - | - | - |
| 3.0 mm | 4.2 ± 1.6 | 3.4 ± 1.4 | 3.0 ± 1.4 | 0.004 | 0.001 | <0.0001 |
| 4.0 mm | 5.2 ± 1.7 | 3.9 ± 1.5 | 3.3 ± 1.5 | <0.0001 | 0.002 | <0.0001 |
| 5.0 mm | 5.5 ± 1.6 | 4.2 ± 1.5 | 3.5 ± 1.6 | <0.0001 | 0.001 | <0.0001 |

P-value: post-hoc test (Bonferroni-Dunn)

- : Not significant

Table 3. Comparison of the masticatory path variables (mean ± SD) in the sagittal view at the 2.0, 3.0, 4.0 and 5.0 mm slice levels during mastication between stages. (n=17)

| Masticatory path variables (Slice level) | Initial stage | Middle stage | Final stage | Statistical significance (P-value) | | |
|---|---|---|---|---|---|---|
| | | | | Initial vs. Middle | Middle vs. Final | Initial vs. Final |
| Closing angle (°) | | | | | | |
| 2.0 mm | 26.4 ± 14.5 | 26.6 ± 10.8 | 26.5 ± 11.8 | - | - | - |
| 3.0 mm | 23.7 ± 12.8 | 26.8 ± 11.4 | 27.1 ± 10.8 | - | - | - |
| 4.0 mm | 24.5 ± 11.0 | 27.1 ± 10.3 | 27.3 ± 9.2 | - | - | - |
| 5.0 mm | 25.3 ± 10.1 | 27.0 ± 10.3 | 27.2 ± 9.1 | - | - | - |
| Opening angle (°) | | | | | | |
| 2.0 mm | 0.7 ± 20.5 | 8.7 ± 16.4 | 5.3 ± 17.8 | - | - | - |
| 3.0 mm | 2.5 ± 16.4 | 2.4 ± 15.7 | -1.4 ± 15.2 | - | - | - |
| 4.0 mm | 0.0 ± 14.7 | -2.5 ± 13.5 | -5.1 ± 14.0 | - | - | - |
| 5.0 mm | -3.4 ± 13.4 | -7.0 ± 13.2 | -10.4 ± 12.8 | - | - | 0.033 |
| Cycle width (mm) | | | | | | |
| 2.0 mm | 1.2 ± 0.6 | 1.4 ± 0.6 | 1.2 ± 0.6 | - | - | - |
| 3.0 mm | 1.5 ± 0.7 | 1.7 ± 0.7 | 1.5 ± 0.7 | - | - | - |
| 4.0 mm | 1.9 ± 0.9 | 1.9 ± 0.9 | 1.7 ± 0.9 | - | - | - |
| 5.0 mm | 2.2 ± 1.1 | 2.0 ± 1.1 | 1.7 ± 1.1 | - | - | - |

P-value: post-hoc test (Bonferroni-Dunn)

- : Not significant

## Figure Legends

### Figure 1

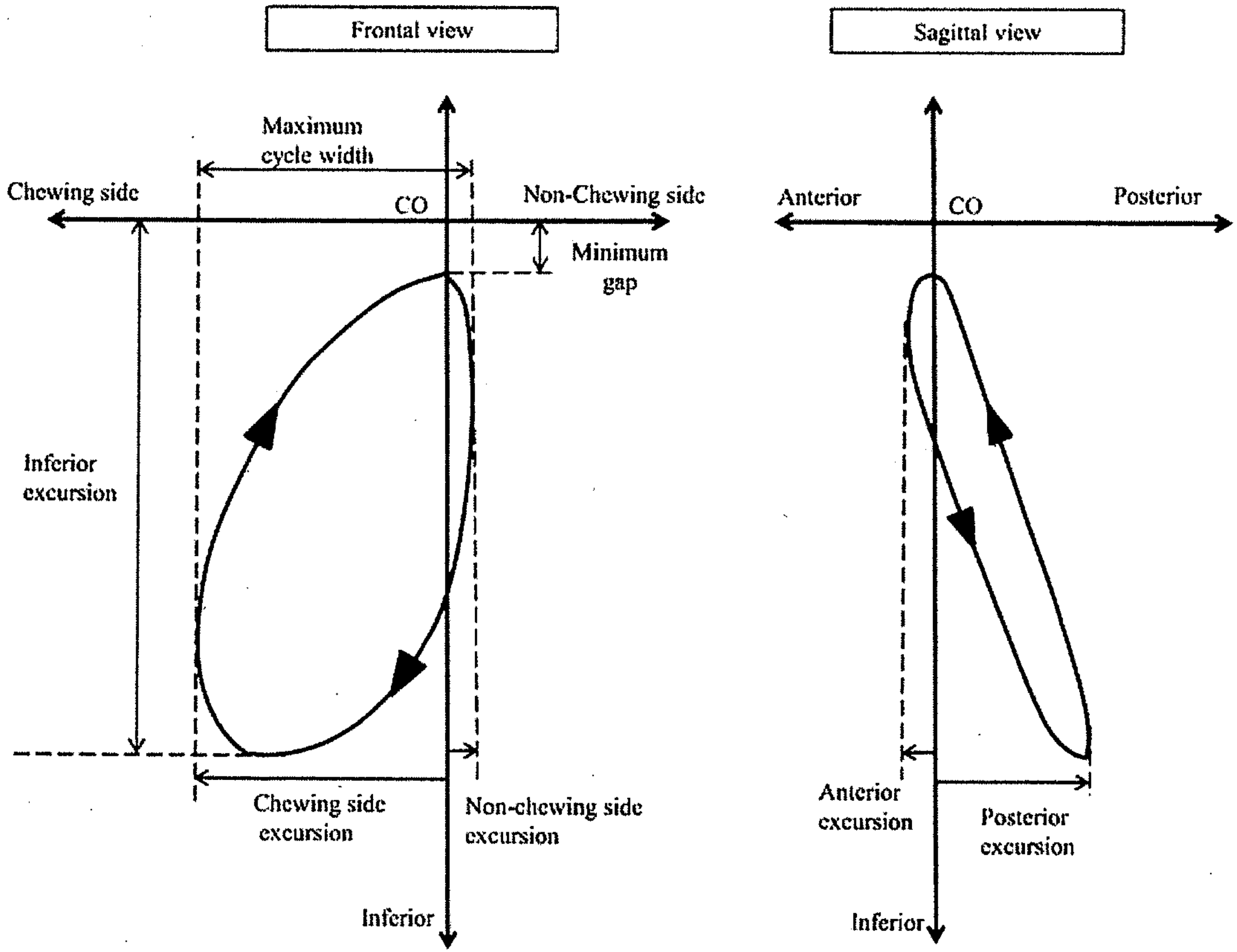
Schematic drawing of the chewing cycle variables in the frontal and sagittal views. CO indicates the centric occlusion.

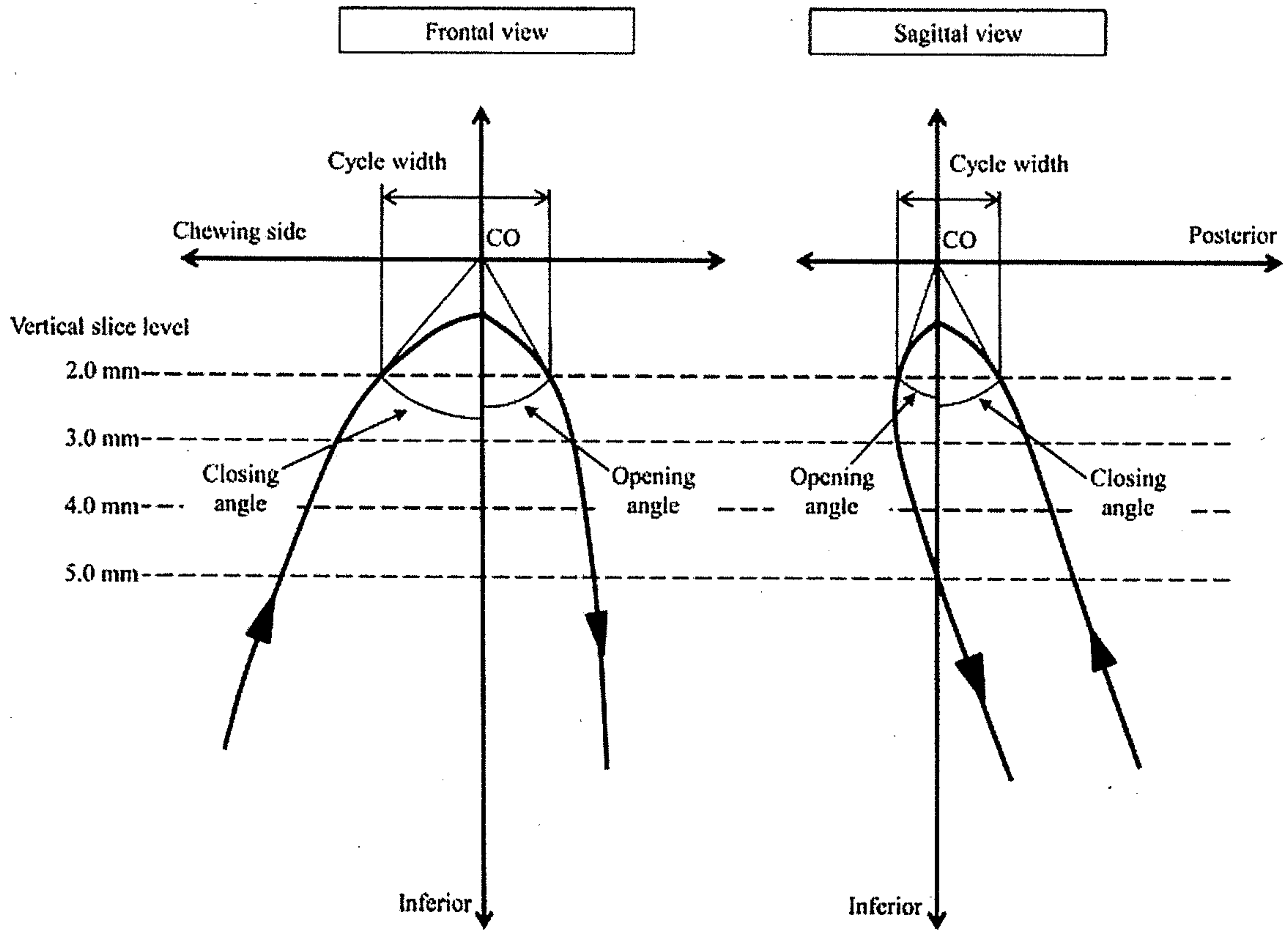
### Figure 2

Schematic drawing of the masticatory path variables in the frontal and sagittal views. The vertical slice level is established at 2.0–5.0 mm below the intercuspation. The closing and opening angle and cycle width at the 2.0 mm slice level are shown.

### Figure 3

The mean masticatory paths of initial, middle, and final stages are shown in the frontal and sagittal views. Solid lines represent the initial stage, double lines represent the middle stage, and the dotted lines represent the final stage in the sequence.


Frontal view
Maximum cycle width
Chewing side
CO
Non-Chewing side
Minimum gap
Inferior excursion
Chewing side excursion
Non-chewing side excursion
Inferior
Sagittal view
Anterior
CO
Posterior
Anterior excursion
Posterior excursion
Inferior


Frontal view
Sagittal view
Cycle width
Chewing side
CO
Vertical slice level
2.0 mm
3.0 mm
4.0 mm
5.0 mm
Closing angle
Opening angle
Inferior
Cycle width
CO
Posterior
Opening angle
Closing angle
Inferior

Non-colour figure3