Analysis of human mastication behavior: a new approach using planar calculations of fragmented chewing sequences

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The aim of this paper is to describe the possibilities of analyzing human mastication. The use of a standardized food model and a standardized protocol using condylographic recordings to create primary data was described elsewhere. Based on the findings of a systematic literature search the current analytic approaches to analyze human mastication showed that a chewing sequence is complex and influenced by many factors. Yet it was not able to establish a valid and robust model to describe human mastication pattern, taken into account known and unknown confounders such as age, sex, number of teeth, and quality of occlusion, either natural or artificial.

A newly developed tool is introduced in this paper. The generic data are created by a jaw tracking system and the complexity of the chewing sequence fragmented in single chewing cycles. Planar calculations in all three spatial planes (sagittal, horizontal, and frontal) are used to describe each chewing cycle. Considerable differences in the calculated areas can be detected. Interindividual distinctions could be assessed, but working and non-working side, initial, median, and terminal chewing cycles of a chewing sequence showed considerable intraindividual differences.

Comparable parameters, created in such an approach, should have the capability for a better understanding of complex mandibular dynamics during chewing. It can be assumed, that better understanding of human mastication, based on measurable values, will support diagnostic and therapeutic efforts for both, clinicians and researchers.

Keywords: human mastication, standard food model, condylography, biomechanics, temporomandibular joint, chewing, planar calculation, segmentation of chewing sequence

Introduction

Movements of the human jaw are complex and hard to describe. Analytic approaches are difficult because of the compound of the possible actions and the multifarious characteristics in individuals. The smoothness of movements was effectively used for a model of human limb actions [14]. Fundamental principle of such an approach is the assumption that the central nervous system as the main controlling unit of muscle activity is looking for optimization of smoothness and harmony of movements.

Smoothness of movement can be quantified by using jerk cost model. In this context jerk is defined as the rate of change in acceleration during a given time. Maximum smoothness and minimum jerk costs are of the same tenor. But even jaw movements during chewing of healthy adult volunteers with good occlusion and class I molar relationship and no clinical signs of dysfunction could not be sufficiently described with the maximum smoothness/minimum jerk cost model [14]. The authors of this study concluded that a cycle by cycle modification of the jaw movement influenced by tongue and lip actions to manipulate the food bolus takes place and causes differences in time profiles for the position of the jaw opening/closing phases between the model and observed data [14]. Studies showed the influence of food properties such as plasticity and elasticity influences the chewing movement patterns. Jaw movements are shaped by different groups of neurons of cortical and brain stem origin. The preprogrammed organization is adapted to rheological behavior of the food. An ongoing feedback circle controls the chewing sequence, based on knowledge and experience, modified by food properties [1, 2, 6, 13]. But chewing muscle feedback alone is not the only input, which influences and modifies mastication. The complexity of masticatory control mechanism includes modifiers such as tongue and cheek activities. Bilateral gum chewing modulates activation in the primary sensory cortex. This activation occurs differentially in each hemisphere, depending on the chewing side preference. This fact supports the existence of short-term memory for a recently practiced movement [8].

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The use of performance indices was emphasized in the literature. A fragmentation model and a masticatory index have been described among others. Chewing performance using a sieve model is based on the outcome and influenced by different factors such as occlusion and missing teeth [7]. Woda et al. concluded in their remarkable study that the use of valid tools for studying groups of individuals is essential and the only way to provide reproducible results. Subjects with impaired mastication are now studied in comparison with a control group characterized by known physiology of mastication. This should lead to the development of masticatory function tests, which should be easy to use in a clinical environment. These data will also assist in the development of a robotic device, which could be either calibrated or trained to simulate the physiological function [13].

The importance of occlusion on masticatory function and chewing pattern was investigated by Gibbs and Lundeen [2, 3]. Chewing pattern is highly dependent on the quality of occlusion. On the other hand, the ability to process the food bolus is reliant on different factors. Yet it remains unclear, in which manner the different factors are interacting.

Studies on the movements of temporomandibular joint are scarce [5]. Coincidence of the opening and closing chewing strokes of the condyles perhaps indicates loading in the joint during chewing. The loading of the joint during chopping of a food bolus on the left or right side was studied. The working side condyle showed shorter movements than the non-working side condyle. Non-working side condyles displayed a synchronized movement pattern, while a significantly smaller number of working side condyles did. These results suggest different loading pattern of working side and non-working side joints [5]. On the base of contemporary knowledge, a standard food model and a standardized test to analyze human mastication were developed and introduced [9–12].

Aim of this study: Condylographic recordings of a chewing sequence produce a mass of data, which are difficult to interpret because of their complexity. Although there are different possibilities to display and analyze these data, a standard procedure for evaluation of mastication pattern is not yet established. Similarly, exact measurements and standard values of human mastication modeling have not been developed. Therefore, a new method using planar calculations of segmented chewing sequences was engineered and will be described in details within this article. This paper should stimulate scientific discussion and encourage further research on this particular field.

Material and method

Source data of condylographic recordings can be exported and used for further examination. Similar export functions are available in most of the software programs for analyzing jaw movement recordings. These data serve as source data within other software programs. One limitation of analyzing mastication pattern with the standard condylographic software is that chewing sequences can be analyzed only en bloc, but not in sequences or each chewing cycle on its own. Dynamic replay of the data is helpful, but the superimposition makes it almost impossible to identify a single chewing cycle. A detailed and close look is limited, it least affected to a great extent.

The following wording is used within this article. A chewing cycle represents one single stroke, while a chewing sequence is the multiplicity of chewing cycles. The new approach to analyze condylographic chewing sequences starts with separation and spread of all chewing cycles. This can be established within a newly developed additional software program. The exported source data are imported and used for the further analysis.

The model food used to analyze mastication should be elastic, possess different degrees of hardness, and be of a minimum size. Based on a conventional mass of gum for manufacturing commercial fruit gum, a standard cylindrical form (height 1 cm, diameter 2 cm) in three different degrees of hardness (soft, hard, medium) was produced (A. Egger' Sohn, Süßwaren und Naturmittel GmbH, Mellergasse 4, A-1230 Vienna, Austria). The degrees of hardness were achieved by adding different quantities of gelatin (edible gelatin SPM 5765, Biogel AG Haldenstrasse 11, CH-6006 Lucerne) to the ground mass (soft: 15.5 g per mass; medium: 23 g per mass; hard: 31 g per mass). The basic practicability of this standardized model food has been described elsewhere.

Masticatory movements are visualized by the use of a paraocclusal clutch and joint path registration. The paraocclusal clutch influences the shearing action of the teeth due to its buccal fixation. However, currently there are no other means of fixing the registration arches. The recordings described in this article were made by the use of the CADIAX®; diagnostic system (GAMMA med. wiss. Fortbildungs GmbH, Josef Brennerstr. 10, A-3400 Klosterneuburg, Austria). All recordings had to be based on a standardized protocol in order to perform an optimal analysis and make interindividual comparisons.

The term curve is used to describe the linear objects, which are not necessarily straight, but a one-dimensional continuum. A plane curve is either a curve within a given plane or a projection of a space curve. A space curve may pass through any region of a three-dimensional space. Several options are provided by engineering mechanics to explain the path of a particular measuring point in space. Paths in space can be parameterized by time, i.e., every point of an illustrated curve can be identified and characterized by time. Such paths are recognized as trajectory. A trajectory is the path a moving object follows through space. The position of the object over time represents one possibility. In contrast, factor time is void for tracking curves. In this respect, track (path) is defined as uniformly continuous mapping of a real and realistic interval within a topological space. The figure of such tracks results in tracking curves. Within this study, we used the projection of the trajectory of the hinge axis on three different planes (sagittal, horizontal, and frontal). Factor time was used to localize start and end point of a chewing cycle.

Results

The condylographic generic data are exported and are now available for further analysis (Fig. 1). Considering the compound diagram of a chewing sequence, it is evident that the amount and complexity of the data handicaps a detailed and particular analysis (Fig. 2). The separation and identification

CC #	LCC start	LCC end	L_XZ	L_XY	L_YZ	RCC start	RCC end	R_XZ	R_XY	R_YZ
1	3,5	4,5	0,58	0,35	0,24	3,9	4,8	2,06	0,79	0,58
2	4,5	5,3	0,64	0,27	0,28	4,8	5,6	1,11	0,08	0,25
3	5,3	6,2	0,76	0,62	0,89	5,6	6,4	1,57	0,46	0,67
4	6,2	7,0	1,06	1,5	1,64	6,4	6,5	0	0	0
5	7,0	7,9	0,78	0,11	0,13	6,5	7,1	2,45	1,94	1,14
6	7,9	8,9	0,63	2,21	2,57	7,1	7,2	0	0	0
7	8,9	10,0	0,29	0,05	0,17	7,2	8,1	1,38	0,2	0,26
8	10,0	10,6	0,29	0,23	0,29	8,1	9,2	0,57	4,03	2,19
9	10,6	11,4	0,18	1,43	1,86	9,2	9,3	0	0	0
10	11,4	12,2	0,05	0,06	0,08	9,3	10,1	1,57	0,42	0,62
11	12,2	12,9	0,41	0,2	0,22	10,1	10,2	0	0	0
12	12,9	13,5	0,47	0,13	0,14	10,2	10,9	1,54	0,5	0,36
13	13,5	14,5	2,2	1,5	1,56	10,9	11,6	1,31	2,68	1,68
14	14,5	15,4	0,64	0,06	0,06	11,6	12,5	0,36	0,22	0,1
15	15,4	16,2	1,23	0,82	0,81	12,5	12,6	0,03	0,02	0,03
16	16,2	17,0	2,61	3,44	3,51	12,6	13,0	0,02	0,01	0,03
17	17,0	0,0	0	0	0	13,0	13,1	0	0	0
18	0,0	0,0	0	0	0	13,1	13,6	0,13	0,09	0,13
19	0,0	0,0	0	0	0	13,6	13,8	0	0	0
20	0,0	0,0	0	0	0	13,8	14,7	2,68	2,3	1,77
21	0,0	0,0	0	0	0	14,7	14,8	0	0	0
22	0,0	0,0	0	0	0	14,8	15,7	1,18	0,34	0,34
23	0,0	0,0	0	0	0	15,7	16,3	0,64	0,23	0,27
24	0,0	0,0	0	0	0	16,3	16,4	0	0	0
25	0,0	0,0	0	0	0	16,4	17,2	1,9	5,23	3,27
26	0,0	0,0	0	0	0	17,2	0,0	0	0	0

Fig. 1: Source data, exported from CADIAX® and displayed in a table. Time is displayed in seconds (LCC start, LCC end, RCC start, RCC end). Area is reported in square millimeter (L_XZ, L_XY, L_YZ, R_XZ, R_XY, R_YZ). CC# Number of chewing cycle; LCC start start time of chewing cycle on the left side; RCC start start time of chewing cycle on the right side; LCC end stop time of chewing cycle on the left side; RCC end stop time of chewing cycle on the right side; L_XZ area of a left chewing cycle, projected on XZ plane; R_XZ area of a right chewing cycle, projected on XZ plane; L_XY area of a left chewing cycle, projected on XY plane; R_XY area of a right chewing cycle, projected on XY plane; L_YZ area of a left chewing cycle, projected on YZ plane; R_YZ area of a right chewing cycle, projected on YZ plane

Fig. 2: Mastication pattern: a chewing sequence of a healthy volunteer (male, 49 years, green standard food model, both side chewing, for details see text)

of each chewing cycle within a chewing sequence is crucial and a pre-condition for further steps. Each single chewing cycle should be describable, calculable, and comparable with others. The division of the chewing sequence in different sections (e.g., initial, intermediate, and terminal) and the

utilization of descriptive parameters for such sections are further alternatives of this new approach.

A newly developed software tool fulfills these requirements. The generic data of a chewing sequence are imported. First, the chewing sequence is displayed in toto. Every

Fig. 3: (a) A chewing sequence transferred to the newly developed software tool. Each chewing cycle can be identified and highlighted. (b) Chewing sequence transferred to the new software tool. The chewing cycles are marked automatically. (c) Manual correction of the location of the chewing cycles. The start of each chewing cycle can be selected manually, shifted or deleted. It is possible to overrule the automatic presetting (for details see text)

Fig. 4: (a) Mastication pattern: the chewing sequence of two healthy volunteer; a remarkable difference in all displayed aspects is obvious. (b) Mastication pattern: a particular chewing cycle (#11) of two healthy volunteer is highlighted; a remarkable difference in all displayed aspects is obvious (for details see text)

chewing cycle can be identified and will be highlighted within the tracing (Fig. 3a). An automated detection of start and endpoint of each chewing cycle is performed immediately after uploading the generic data (Fig. 3b). A manual re-adjustment can be performed to locate each chewing cycle more precise (Fig. 3c).

Analyzing different chewing cycles, the unequal circumference in sagittal, frontal, and cranial plane is remarkable (Fig. 4a). To generate characterizing parameters for the spatial areas in the three planes seems to be the first step to create comparative measurements. After the successful localization of a chewing cycle, the area in sagittal, frontal, and cranial area are calculated, units in square millimeter (Fig. 4a, b). It could be demonstrated that different skeletal and dental classes have diverse functional archetypes in sagittal, transversal, and frontal aspects with the possibility to describe the distinctions with such spatial calculation. In addition, the areas can be used to calculate ratios (for example: sagittal/transversal, or sagittal/frontal). The allocation of an individual to a functional chewing type, independent of dental and/or skeletal classification, could

be integrated part of a functional diagnostic and classification. Comparing the ratios of a single chewing cycle (e.g., chewing cycle 11) of two different volunteers (volunteer A, skeletal and dental class I; volunteer B, skeletal class II, dental class II/1), the remarkable difference is obvious. Volunteer A has a ratio xz/xy of 4.7 ($xz = 0.75 \text{ mm}^2$, $xy = 0.16 \text{ mm}^2$), while volunteer B shows a ratio xz/xy of 0.32 ($xz = 0.79 \text{ mm}^2$, $xy = 2.44 \text{ mm}^2$) on the working side. The difference of the ratios on the non-working side is even more distinct (Fig. 5).

The division of the chewing sequence in different sections and the utilization of descriptive parameters, e.g., ratios xz/xy may serve for additional analytic possibilities. The chewing sequence of a healthy volunteer is separated into four sections; the mean value for the ratio xz/xy is calculated for each section. The chewing sequence was generated with the hard standard food model [9]; the left side is the working side. Recording time is 18 sec. While a decrease of the ratio xz/xy occurs on the right side (non-working side), an increase of the ratio xz/xy turns up on the left side (working side) (Fig 6).

Fig. 5: Analytic sequence and calculation of areas xz , xy , and the ratio xz/xy (for details see text)

#CC	Ratio xz/xy right	Ratio xz/xy left	Mean right	Mean left
0	0,001	0,001		
1	2,87	1,30		
2	2,59	0,07		
3	2,69	0,03		
4	2,77	1,41		
5	2,98	1,66	2,31	0,58
6	2,11	1,25		
7	2,05	0,55		
8	2,05	0,15		
9	2,47	0,88		
10	1,95	1,35	1,98	0,84
11	1,3	0,25		
12	2,47	2,84		
13	1,43	0,40		
14	2,17	0,83		
15	2,05	0,18	1,88	0,90
16	1,18	0,36		
17	1,85	1,10		
18	1,2	0,88		
19	1,43	0,66		
20	1,8	2,12	1,49	1,02

Fig. 6: Possible analytic approach to describe a chewing sequence (For details see text)

Conclusion

A new method of planar description for chewing sequences and chewing cycles is introduced. Significant differences of the two-dimensional enlargements in sagittal, transversal, and frontal aspect of the condylography of chewing sequences have been described [9–12]. There is a reasonable basis to assume a correlation between the transverse extent of chewing movements and some skeletal and dental/occlusal factors, although further research has to be conducted to be able to draw a final conclusion. The influence of skeletal morphology on chewing pattern is demonstrated in Fig. 5. The calculation of the circumscribed area seems to be able to produce a numerical value to describe mastication pattern more detailedly. The two-dimensional specification of the area, determined by a chewing cycle, provides new information on the mandibular dynamics during mastication. The sequential analysis of the mastication sequence (e.g., 1st, 2nd, and 3rd; initial vs. final chewing strokes; etc.) should be used not only in clinical, but also in experimental settings.

In such a way the created comparable parameters should have the capability to understand complex mandibular dynamics better. It can be assumed, that a better knowledge of human mastication, based on measurable values, will support diagnostic and therapeutic efforts for both, clinicians and researchers.

Conflict of interest

The authors declare that there is no conflict of interest.

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All participants gave informed consent after receiving a full explanation of the goals and execution of the study. A preliminary report of this manuscript was given as an oral presentation by the corresponding author at the IAAID Asia Meeting International Conference on Occlusion, Tokyo, Japan on September 18–22, 2009.

References

- [1] Foster KD, et al. Effect of texture of plastic and elastic model foods on the parameters of mastication. *J Neurophys* 2006;95:3469–79.
- [2] Gibbs CH, et al. Occlusal forces during chewing – Influences of biting strength and food consistency. *J Prosth Dent* 1981;46(5):561–7.
- [3] Gibbs CH, et al. Comparison of typical chewing patterns in normal children and adults. *JADA* 1982;105:33–42.
- [4] Lassauzay C, et al. Variability of the masticatory process during chewing of elastic model foods. *Eur J Oral Sci* 2000;108:484–92.
- [5] Naeije M, Hofman N. Biomechanics of the human temporomandibular Joint during chewing. *J Dent Res* 2003;82:528–31.
- [6] Peyron M-A, et al. Effects of increased hardness on jaw movement and muscle activity during chewing of visco-elastic model foods. *Exp Brain Res* 2002;142:41–51.
- [7] Schneider G, Sender B. Clinical relevance of a simple fragmentation model to evaluate human masticatory performance. *J Oral Rehab* 2002;29:731–6.
- [8] Shinagawa H, et al. Chewing-side preference is involved in differential cortical activation patterns during tongue movements after bilateral gum-chewing: a functional magnetic resonance imaging study. *J Dent Res* 2004;83:762–6.
- [9] Slavicek G, et al. A novel standard food model to analyze the individual parameters of human mastication. *IJSOM* 2009;2(4):163–74.
- [10] Slavicek G, et al. Fallstudien zur Analyse des Kauens Teil 1: die Standardanalyse. *Stomatologie* 2009;106:119–29.
- [11] Slavicek G, et al. Fallstudien zur Analyse des Kauens Teil 2: spezielle Analysemöglichkeiten. *Stomatologie* 2009;106:137–48.
- [12] Slavicek G, et al. Fallstudien zur Analyse des Kauens Teil 3: Analyse von Höckerbewegungen. *Stomatologie* 2009;107: in print.
- [13] Woda A, et al. Adaptation of healthy mastication to factors pertaining to the individual or to the food. *Physiol Behav* 2006;89:28–35.
- [14] Yashiro K, et al. Smoothness of human jaw movement during chewing. *J Dent Res* 1999;78:1662–8.