Accepted Manuscript

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PII: S0003-9969(17)30237-6
DOI: http://dx.doi.org/doi:10.1016/j.archoralbio.2017.07.016
Reference: AOB 3954

To appear in: *Archives of Oral Biology*

Received date: 11-6-2017
Revised date: 21-7-2017
Accepted date: 23-7-2017

Please cite this article as: Ferreira Claudia Lúcia Pimenta, Zago Matteo, de Felício Cláudia Maria, Sforza Chiarella.AN INDEX FOR THE EVALUATION OF 3D MASTICATORY CYCLES STABILITY.*Archives of Oral Biology* http://dx.doi.org/10.1016/j.archoralbio.2017.07.016

AN INDEX FOR THE EVALUATION OF 3D MASTICATORY CYCLES STABILITY

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Highlights:

- The variability in the motor behavior of chewing can impair its evaluation
- We devised a synthetic index to evaluate chewing cycles starting from kinematic data
- The index could complement clinical assessments
- The index could provide data to plan the rehabilitation of masticatory function

Abstract

Objectives: to introduce an index (Masticatory Stability Index, MSI) to analyze the stability of chewing cycles in standardized conditions and test it in a group of patients with subclinical mild temporomandibular disorder (TMD).

Design: 23 subjects with mild subacute TMD and 21 healthy subjects were involved; they all responded to a questionnaire about signs and symptoms of TMD (ProTMDmulti) and underwent a myofunctional orofacial evaluation with scores, using the protocol of orofacial myofunctional evaluation with scores (OMES). Their mandibular kinematics was assessed with a 3D motion capture system during deliberate unilateral gum chewing. The MSI was computed synthesizing the information contained in nine kinematics parameters into a single global figure. Patients' and controls' MSI were compared considering the preferred and non-preferred chewing side using a 2-way ANOVA (factors: group, side).

Results: Together with a lower total score of myofunctional orofacial status, the TMD group showed a reduced stability based on MSI ($p<0.05$).

Conclusions: the MSI is an efficient method to measure the stability of the masticatory cycles. These preliminary results encourage validating the index on a larger sample. The variability in the motor behavior of chewing can impair the objectivity of its evaluations in several types of patients, including those with TMD. The MSI could be useful to complement clinical assessments, providing data for planning the rehabilitation of masticatory function in these patients.

Key Words: Temporomandibular joint disorders; Mastication; Chewing cycle; Kinematics; Motion

1. Introduction

Mastication comprises a number of coordinated spatiotemporal events of various structures (e.g., alternating contraction of the jaw-closing and jaw-opening muscles, tongue movements), which are naturally executed with a wide variability (Ferrario et al., 2006; Kordass, 2006) depending on the morphofunctional and neuromuscular status of the evaluated subject.

Since this function may reflect the condition of various elements of the stomatognathic system, the quantitative evaluation of chewing can have an important impact in the assessment of disorders affecting this system (Kuwahara, 1989), as for example occurs in cases of patients with dentofacial deformity (Takeda et al., 2009), temporomandibular disorders (TMD) (De Felício et al., 2013; Ferreira et al., 2016) or those with Parkinson’s disease (Ribeiro, Campos & Rodrigues Garcia, 2016).

The TMD are a group of musculoskeletal and neuromuscular conditions involving the temporomandibular joints, masticatory muscles and associated tissues; among their signs and symptoms they may include difficulties in orofacial functions (Greene, Klasser & Epstein, 2010).

Kinematic analysis is a useful tool to accurately detect the trajectory and the "quality" of jaw movements and deviations. The three-dimensional jaw movements during mastication can be analyzed by means of several specific spatiotemporal parameters of each masticatory cycle, as maximum range of motion, total cycle area, opening and closing maximum velocity, cycle duration, vertical, posterior, and right and left jaw movements (Buschang, Hayasaki & Throckmorton, 2000; Ferrario et al., 2006; Lepley et al., 2010; Radke, Kull & Sethi, 2014). Also, the opening and closing phases of the chewing cycles have been subjectively classified in various characteristic patterns, according to the shape and direction of the trajectory, suggesting the existence of relations between the representative types of mandibular trajectories and malocclusions, and even with the presence of TMD (Naeije & Hofman, 2003; Takeda et al., 2009; Kobayashi et al., 2009).

Considering the potential ability of selected descriptors of chewing cycles to differentiate among normalcy and various pathologies, but also the variability inherent in each subject, different methods have been used to study within-subject variability, which include the selection of “representative” cycles and the use of statistical approaches (Buschang, Hayasaki & Throckmorton, 2000; Wintergerst, Buschang & Throckmorton, 2004; Ferrario et al., 2006; Wintergerst, Throckmorton, & Buschang, 2008; Shiga et al., 2009). Furthermore, since the stability of masticatory movements can also be influenced by the different foods and textures, studies have also been carried out in this sense (Shiga et al., 2003; Wintergerst, Throckmorton, & Buschang, 2008; Shiga et al., 2012).

Specifically, authors introduced new methods to evaluate the chewing cycles and proposed a statistical approach to identify and select the most representative cycles from a sequence using cycle duration, range and shape (Buschang, Hayasaki & Throckmorton, 2000). This approach reduced the random within-subject variation in chewing cycle kinematics while enhancing inter-subjects variations (Wintergerst, Buschang & Throckmorton, 2004). Other investigators simply used the standard-deviation (SD) as an indicator of the stability of the movement path (opening lateral, closing lateral, and vertical components) (Shiga et al., 2009).

The analysis of the movement stability is a recognized tool in instrumented gait analysis (Heiderscheit, 2000; Baker et al., 2009). Recently the "*gait variability index*" was developed and successfully used to objectively evaluate the variability of gait through comparisons with classically used evaluation tools (Gouelle et al., 2013).

In this sense, a single index of stability summarizing a set of spatiotemporal parameters extracted from the masticatory cycle would be of great interest to evaluate specific diseases, such as the TMD. The aim of this study was to develop and present the Masticatory Stability Index (MSI), extending the work of Gouelle et al. (2013), and test it in a group of subclinical patients with mild TMD. The hypothesis is that this index may reflect a greater variability/ instability of the cycles in these patients compared to asymptomatic subjects.

2. Materials and methods

2.1. Subjects

This study included 44 subjects, 23 with subclinical mild TMD (TMD: 9 men and 14 women; mean age 21.0 ± 3.0 years) and 21 without TMD complaints (Healthy participants, HP: 8 men and 13 women; mean age 21.43 ± 4.6 years), matched by age and sex. The volunteers were students and staff at the University of Milan; after detailed explanation of the experiment they all signed an informed consent before the beginning of the study. The data were collected according to the Declaration of Helsinki and to the norm of the Italian University where the research was carried out.

For the sample selection all volunteers answered a validated self-judgment questionnaire to detect the presence and to measure the severity of signs and symptoms of TMD (ProTMDmulti-part II questionnaire; De Felício, Melchior & da Silva, 2009; De Felício et al., 2012). Then they were evaluated by the same experienced examiner, according to Research Diagnostic Criteria for TMD (RDC/TMD) – Axis I (Dworkin & LeResche, 1992).

In the TMD group, subjects with mild severity of signs and symptoms of TMD according to ProTMDmulti-part II (mean 22.78, SD 34.21), and that have not previously sought care to TMD, were included. All patients presented disk displacement with reduction only (N = 17), or combined with another classification: arthralgia (N = 2), or arthralgia + myalgia (N = 4), according to RDC/TMD.

In the Healthy group, subjects with good general health and absence of signs and symptoms of TMD according to ProTMDmulti-part II (mean 3.57, SD 5.27) and RDC/TMD were included.

Exclusion criteria for both groups were: tooth absence, loss of posterior support, dental pain or periodontal problems, cast restorations and cuspal coverage, pregnancy, neurological or cognitive deficit, previous or current tumors or traumas in the head and neck region, current orthodontic, orofacial myofunctional or TMD treatment, current use of analgesic, anti-inflammatory and psychiatric drugs.

2.2. Data Collection

2.2.1. Clinical evaluation of orofacial myofunctional status

An experienced speech pathologist evaluated appearance/posture, mobility performance of stomatognathic system structures and functions, i.e. respiration, deglutition, bite, type of chewing and signs of alteration during chewing, using the OMES Protocol (De Felício, Medeiros & Melchior, 2012). The total score of orofacial myofunctional status was obtained from the sum of the scores attributed to each item, with a range from 32 to 103 (worst to best orofacial myofunctional condition).

Specifically, to clinically test chewing, subjects were instructed to chew in their usual manner (free chewing) a chocolate-flavored stuffed cookie (Bono® - Nestlé, São Paulo, SP, Brazil). The examiner counted the number of masticatory strokes and measured the time spent to consume the cookie (with a chronometer: Q&Q Stop Watch HS43, Mailand, China), starting to count and measure after the first bite and stopping after the final deglutition of each portion. The total number of strokes and total time was obtained by summing the partial times.

The masticatory type was classified as follow, according to the expanded OMES-E protocol (De Felício et al., 2010): bilateral and alternate chewing; simultaneously bilateral chewing (masticatory strokes were distributed on both sides of the oral cavity, 95% of the times); unilateral preference grade 1 (masticatory strokes performed on the same side 61–77% of the times); unilateral preference grade 2 (masticatory strokes performed on the same side 78–94% of the times); chronic unilateral chewing (masticatory strokes performed on the same side 95–100% of the times). Any of the last three conditions was interpreted as preferred chewing side (PS) for the subsequent kinematic analysis.

2.2.2. Mandibular kinematics

A second independent examiner performed the kinematics data collection and analysis.

Subjects were evaluated sat on a chair without headrest, with the head in natural position. The mandibular motion was tracked by means of an optoelectronic motion capture system (BTS Spa, Italy), using three passive markers (diameter: 5 mm) positioned on the three corners of an equilateral triangular stainless steel extraoral device (side 40 mm, weight 2 g); this tool was fixed on the mandibular anterior gingiva using a surgical adhesive (Stomahesive; Convetec Inc., UK), providing a mandibular reference system (Mapelli et al., 2009).

A previous anatomical calibration involving a further passive mandibular marker (diameter: 3 mm) manually located on the midline incisor edge (inter-incisor point); allowed the reconstruction of a dental (occlusal) landmark (Figure 1), related to the extraoral system (Mapelli et al., 2009). Two condylar reference points, identified by palpation, and a third on the forehead, constitutes the head inertial reference frame.

First, each subject received a sugarless chewing gum (1.5 g; Mentadent Integral, Unilever Italia, Milan, Italy), to get used to chew it unilaterally with the recording apparatus. Then, the participants received a new chewing gum and after pre-softening it, the recordings were made under the following conditions: (1) 30 seconds of unilateral chewing on the right side; (2) 30 seconds of unilateral chewing on the left side. Each trial had to start and conclude with the teeth in intercuspal position, controlled by the examiner to ensure that the subject returned to the initial position.

2.2.3. Masticatory Stability Index

An algorithm was developed to locate and retain cycles. Cycle inclusion criteria were: start from centric occlusion, duration of at least 300 ms, vertical range of motion higher than 3 mm and belonging to the same side. The first five cycles were excluded from the analyses to avoid movements that involve the initial positioning of the bolus over the teeth.

Custom Matlab® software (Mathworks Inc, USA) allowed for the computation of a set of parameters: (i-iii) duration, velocity and length of the masticatory cycle (on the frontal plane); (iv) area subtended by the trajectory; (v) inclination of the trajectory (slope of the eigenvector of the coordinates matrix) with respect to the vertical axis; (vi) shape of the trajectory, measured as λ_2/λ_1, where λ_1 and λ_2 are the first and the second eigenvalues of the $2{\times}n$ matrix describing the cycle (n is the sample number); (vii-ix) ranges of motion (RoM) along the three (x, y, z) spatial directions.

Twenty most representative masticatory cycles were retained, according to the methodology previously described by Wintergest, Buschang & Throckmorton (2004). Then, the mathematical procedure developed by Gouelle et al. (2013) was followed to quantify the fluctuation magnitude of spatiotemporal chewing parameters: for every parameter on each side, the mean and SD of the normalized sequence of differences between consecutive values were computed. Thus, 18 parameters were obtained from the initial 9 spatiotemporal variables for each side. The first Principal Component factor was computed performing the Principal Component Analysis on a [44 subjects x 36 variables] data matrix. The correlation coefficients c_n between PC1 (First Principal Component) and each variable p_n constitutes the weighting of each variable. Table 1 reports the parameters weighting, expressed as average correlation of each variable with the first Principal Component obtained from the whole dataset. Cycle length and vertical range of motion had the highest values (mean correlation coefficients, 0.9), while the inclination was poorly related (mean coefficient, 0.03).

For a subject *i*,

$$s_i = \sum_{1}^{18} p_n \cdot c_n$$

If s_{HP} is the mean sum in the healthy participants, a distance $d_{i,HP}$ between the parameters of a subject *i* and those of the HP can be defined as:

$$d_{i,HP} = \|s_i - s_{HP}\|$$

A raw index is computed as:

$$\boldsymbol{MSI_{raw,i}} = \mathbf{ln}(\boldsymbol{d_{i,hP}})$$

Next, the number of SDs separating the raw score of the *i*-th subject from the raw score of the HP (*z*-score) is computed:

$$zMSI_{raw,i} = \frac{MSI_{raw,i} - mean(MSI_{raw,HP})}{SD(MSI_{raw,HP})}$$

The final index is then obtained as:

$$MSI_i = 100 - 10 \cdot zMSI_{raw,i}$$

By definition, the mean score and SD of the reference population are 100 and 10. A MSI≥100 means that the patient has a level of variability similar to that of the HP. Each 10 points difference corresponds to a separation of one SD from the HP score, indicating that the variability of the subject is greater in the patient than in normal chewing, and therefore that the stability is reduced.

To define the preferred chewing side (PS) and non-preferred chewing side (NPS), both the results of the individual preference and the clinical evaluation of the mastication (OMES-E protocol, as described above) were considered. When subjects chewed with bilateral and alternated pattern, the selected side to the analysis was the one elected by the subjects as their preferred chewing side.

2.3. Statistical Analysis

Descriptive statistics were computed for all variables separately for each test. Mann-Whitney Test was used for the comparisons between groups considering the scores of the signs and symptoms severity, difficult to chewing and myofunctional orofacial status. The 2-way ANOVA (factors: group, side) was used to test differences in MSI. The level of significance was set at 5% for all statistical analyses.

3. Results

The TMD group presented a lower total score of myofunctional orofacial status (Mann-Whitney Test, $p < 0.01$) and mobility category ($p < 0.05$) than the Healthy group according to OMES protocol (Table 2). In contrast, the appearance/ posture and function scores were similar in the two groups.

The MSI showed that TMD patients had a lower movement stability while chewing a gum on both sides (2-w factorial ANOVA, $p<0.05$, Table 3). No significant differences between the sides or group x side interactions were found ($p>0.05$).

4. Discussion

The kinematics of masticatory cycles is the composite result of the interaction between the neuromotor control and the breakdown of food. Intra-subject variability offers a great potential for understanding the neuromuscular control of chewing, also helping to explain the pathophysiology of certain diseases (Wintergerst, Buschang & Throckmorton, 2004).

The variability between individuals and the food are important features of the physiology of human mastication (Pörschel & Hofman, 1988; Hennequin et al., 2005) and certain reproducibility exists for each subject (Peyron & Woda, 2006), while in subjects with important disorders, the masticatory cycle patterns begin to resemble chaos (Radke, Kull & Sethi, 2014). It is also known that a low reproducibility, and thus a poor stability between the masticatory cycles, may reduce the skill and objectivity of clinical and experimental evaluations of normality/abnormality of jaw movements, reducing the power of statistical tests (Wintergerst, Buschang & Throckmorton, 2004; Yashiro & Takada, 2004).

The MSI index proposed in this study was developed to objectively quantify, by means of a single value (which summarizes nine spatiotemporal parameters), the stability of the chewing cycles. In the current paper, the MSI has been tested in patients with subclinical mild TMD, and showed a statistically significant lower stability of the masticatory function in this group compared to a group of asymptomatic, healthy subjects.

The spatiotemporal parameters selected for this index are those generally evaluated in previous studies involving classical analysis of chewing kinematics, where the subjects/ patients were described by the mean values and standard deviations of the same parameters (Pörschel & Hofman, 1988; Buschang, Hayasaki & Throckmorton, 2000; Wintergerst, Buschang & Throckmorton, 2004; Ferrario et al., 2006; Shiga et al., 2009; Lepley et al., 2010; De Felício et al., 2013; Radke, Kull & Sethi, 2014), but where there was not a synthetic value able to summarize the various interrelated measurements. In the current investigation, we introduced a new single index, which takes several spatiotemporal parameters into account, thus globally describing chewing.

The MSI enabled to quantitatively estimate the similarity of the functional stability of patients with TMD with respect to a healthy population during a standardized chewing test. Therefore, the more the

TMD group varies from the healthy group, the lower their masticatory stability. From this point of view, the MSI may be a useful parameter to estimate the peripheral functional impact, the pattern of neuromuscular recruitment and to infer about the motor control for this function. In the current group of TMD patients, the actual distance of MSI from the reference value of 100 was reduced (1.3 preferred side, 4.5 non preferred side), showing that the kinematic rearrangement of jaw movements, although significant, was minor. It is worth mentioning that these results are consistent with the condition of the current patients, who had subclinical and mild TMD and had not sought any treatment. For the "*gait variability index"* proposed in a previous study, higher differences from normal subjects were found because of the higher gait impairments of the studied subjects as compared to controls (Gouelle et al., 2013). However, we argue that when applied to the chewing patterns of patients with more severe TMD the MSI will provide distinct results as well.

A recent study of gait variability suggested that this analysis may reflect the underlying motor control, being, thus, relevant to quantify changes related to age and to the pathologies in the locomotor system control, as well as to provide a clinical measure of mobility and functional status (Gouelle et al., 2013). Indeed, both chewing and gait are cyclic, rhythmic functions of the human body, and their control is influenced by a central pattern generator, that interacts dynamically with different levels of the central nervous system, integrating sensory information to produce motor commands according to functional demands (Lund, 1991).

It is worth remembering that to avoid the influence of factors which may reduce the stability of movements during chewing, in this study the tests were made with deliberate unilateral mastication of chewing gum. The first reason was that a deliberate unilateral mastication is more stable than the free mastication (Shiga et al., 2003; 2012; Brandini et al., 2011). Recent investigations performed by using functional magnetic resonance imaging (fMRI) found that the right- and left-sided chewing of healthy subjects has no differential brain activation between each other, both showing activation in areas also involved in bilateral occlusion (Lotze, Domin & Kordass, 2016). The second reason was that the chewing gum has minimal physical variation and does not suffer texture changes during the examination period (Shiga et al., 2003).

Alterations in movement stability may indicate how and how much the stomatognathic system is capable to adapt to functional demands. In fact, the interpretation of the "quantity" of stability is also something to be questioned. Often we may think that a higher instability may mean functional faults, interpreted as a neuromuscular incoordination. However, also a very limited variability should be interpreted as reflecting an inadequate functioning, especially suggesting a failure of the stomatognathic system to adapt to the task. Indeed, more monotonous or stereotyped chewing cycles indicate higher risk of permanent wear of anatomical structures (Kordass, 2006).

In the case of the analyzed TMD patients, which could be described as subclinical cases, the instability could be interpreted as an initial adaptation process, in an attempt to prevent discomfort or structural damages (Yashiro, Miyawaki & Takada, 2004; Radke, Kull & Sethi, 2014) or as a process of adaptation to the general principle of the greater functional efficiency and performance (Ogawa, Koyano & Suetsugu, 1997). Moreover, the greater variability in jaw movements in the absence of significant painful symptoms, as verified in the current TMD group, could be an effect of a persistent decrease of the excitability of the facial motor cortex, which is important for refined jaw movements (Bhaskaracharya et al., 2015).

The lower stability could be a result of the orofacial components disabilities. For the control of the involved structures in chewing function, it is necessary that the system handles both the variations found in the properties of food and the need to generate precise orolinguofacial movements (Crane et al., 2013). Indeed, the TMD group had worse general myofunctional status, including changes in mandibular and tongue mobility, in agreement with previous findings (De Felício, Medeiros, Melchior, 2012). It is suggested that such results could partly explain the lower values of MSI in this group.

Occlusal factors may also influence the stability of jaw movements. Generally, subjects with normal occlusion have regular chewing patterns and those with occlusal instability have more irregular patterns, as well as having a poorer masticatory performance (Lepley et al., 2010).

Finally, these results are consistent with the lower severity of symptoms and the subclinical condition of the TMD in the patients. In this sample, only 3 patients reported pain and assigned low scores when asked about it (one in masticatory muscles, one in temporomandibular joints and one neck pain). Possibly, the masticatory function was most influenced by mechanical factors (e.g. disk displacement with reduction) and by a possible neuromuscular incoordination than by the presence of symptoms of pain. This suggests that in these subclinical and mild cases it is important to be aware of some indicative signs of possible future imbalances, including functional changes, such as more variable masticatory cycles. In many cases, these characteristics may be later become apparent and if neglected, i.e. if progressing without diagnosis or treatment, may represent a risk to the health and functional balance of the stomatognathic system (Okeson, 2014).

Obviously, if considered isolated, the value obtained through MSI has no diagnostic value, but when taken together with the other results of clinical evaluation and EMG, can be of great clinical utility to readily depict a patient’s status. Therefore, the stability analysis of the masticatory cycles could be interpreted as a neuromuscular measure of coordination or adaptation for a specific motor task, such as the chewing function.

The described index may also be usefully employed in the evaluation and characterization of masticatory behaviors on other types of patients, such as children with open bite or orthodontic treatment, adults with dentofacial deformities, dentures wearers, Parkinson’s disease and others.

Within the limitations of this study, our results, obtained from patients with subacute and mild TMD, support the use of MSI as an efficient method to measure the stability of the masticatory cycles. The current preliminary results encourage validating the index on a larger sample. However, prior to claim its general validity, it is still necessary to raise a large amount of normative data in order to enable its use in a clinical environment - where a matching control group may be missing - and to carry out further investigations focused on more severe and long lasting TMD. Moreover, building a normative, "open-access" database that could be shared between institutions (as in gait analysis), could be of great interest to the development of the method.

In conclusion, MSI could be useful to provide measures for future studies, including measuring the effects of rehabilitation programs with motor and functional training of patients with TMD.

COMPLIANCE WITH ETHICAL STANDARDS

Conflict of Interest: Dr Pimenta Ferreira declares that she has no conflict of interest. Dr Zago declares that he has no conflict of interest. Dr de Felício declares that she has no conflict of interest. Dr Sforza declares that she has no conflict of interest.

Funding source: CLPF received a Post-doctoral fellowship from the Program Science Without Borders from the National Council for Scientific and Technological Development (CNPq), Brazil, Process N^{o} 246658/2012-6.

Funding sources

Ethical approval: All procedures were noninvasive and not painful, and were made in accordance with the ethical standards of the institutional research committee (process number 2013/CS_CPF Dept biomedical sciences Univ Milano) and with the 1964 Helsinki declaration and its later amendments. Informed consent was obtained from all individual participants included in the study.

Informed consent: Informed consent was obtained from all individual participants included in the study.

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Figure caption

Figure 1: Reconstruction of dental (occlusal) landmark's trajectories on the frontal plane for one Healthy (left) and one TMD subject (right). The black thick line is the average masticatory course.

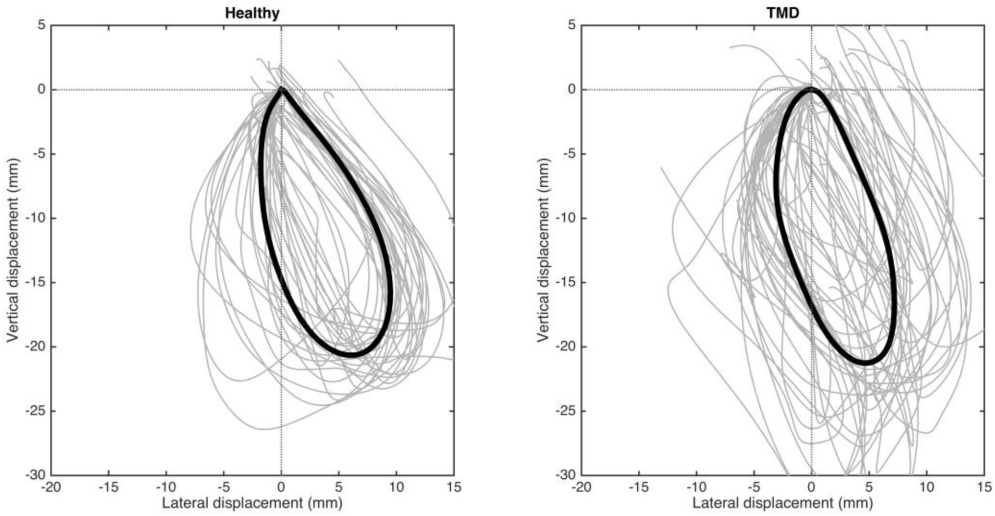

Table 1. Parameters weighting, expressed as average correlation with the first Principal Component obtained from the whole dataset.

	Correlation with the principal factor	
Calculated parameter	Mean	SD
Duration	0.71	0.64
Velocity	0.71	0.62
Length	0.90	0.91
Area	0.51	0.66
Inclination	0.03	0.07
Shape	0.50	0.40
RoMx – anterior-posterior	0.77	0.71
RoMy – vertical	0.89	0.83
RoMz – right-left	0.62	0.55

Table 2. Mean, standard deviation and comparisons between groups for the orofacial myofunctional status, according to OMES protocol

Parameter	Healthy (N = 21)		TMD (N = 23)		p
	Mean	SD	Mean	SD	
Appearance/Posture score	15.43	1.47	14.57	1.78	0.087
Mobility score	51.81	3.97	48.09	3.79	0.004
Functions score	26.24	1.26	25.52	1.59	0.125
OMES total score	94.38	4.33	89.08	5.03	0.001

p: probability on Mann-Whitney test ($p<0.05$).

Table 3. Masticatory Stability Index (MSI) computed on Healthy and TMD participants for both the Preferred and Non-Preferred Chewing Side (PS and NPS, respectively).

Group	MSI, PS		MSI, NPS	
	Mean	SD	Mean	SD
Healthy	100.0	10.0	100.0	10.0
TMD	96.3	5.3	95.2	5.4

$p=0.012$, 2-way ANOVA, significant differences on the group factor.