Characteristics of Chewing: An Update of the Literature

Características de la Masticación: Una Actualización de la Literatura

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ABSTRACT: Chewing is the first step in the digestion process in mammals. It is a highly coordinated process with a complex sensorimotor activity, the aim of which is to prepare foods for the formation of the alimentary bolus and then swallowing. It is a process with defined stages and patterns of movement that adapt to changes derived from the environment or the individual. Here, we review the main characteristics of chewing, including aspects of the physiology and characteristics of the mechanics of mandibular movement. We highlight the latest advances reported and the new methodologies used for a chewing analysis, which has made it possible to collect more precise and reliable data. Thus, we will see how the new technologies have provided a better understanding of this function and its relation to aspects of an individual's general health such as nutrition or the appearance of neurodegenerative diseases. Also, in this review we emphasize the close relation that exists between chewing and a person's quality of life.

KEY WORDS: chewing, chewing cycles, mandibular movement, nutrition, neurodegenerative diseases, quality of life.

INTRODUCTION

Chewing is the first and most important step in the digestion process in most mammals. It is characterized by a complex sensorimotor activity that consists of rhythmic movements of opening and closing of the jaw, the objective of which is to reduce, grind and moisten foods for the formation of the bolus that can be swallowed and the digestion process continued (Lund, 1991; Cho *et al.*, 2015; Isabel *et al.*, 2015; Iguchi *et al.*, 2015).

Chewing is a conditioned process that depends on the position, morphology and presence of the teeth in the mandible and maxilla. It is a learned and semiautomatic process that occurs after the teeth have erupted and that is gradually assimilated by the nervous system, becoming a highly stereotyped event but one dependent on neurosensory feedback (Dellow & Lund, 1971). The development of mastication patterns is related to the eruption of the first teeth, those that will give the sense of mandibular position to the baby, a previously nonexistent condition due to the lack of these structures. This leads to the development of the first dental contacts, causing in turn the first mandibular movements with little coordination. As time passes, the first masticatory reflexes will be conditioned and perfected with the appearance of proprioception (periodontal, articular, of the tongue and the mucosa), which will ultimately make it possible to develop a mature masticatory movement with maximum functionality and efficiency.

In addition to being a semiautomatic process, chewing is a highly coordinated event. This coordination prevents any type of damage to the components of the system in which strong forces intervene as the result of the action of the masticatory muscles. This complex motor activity is based on conditioned reflexes closely related to occlusion, the periodontium, temporomandibular joints (TMJs), masticatory muscles, palate and salivary glands (Soboleva *et al.*,2005).

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In chewing, it is also possible to distinguish different types of movement patterns, which are closely related to type of food being chewed. For example, when chewing hard food, the lateral movements of the jaw predominate, whereas with soft food chewing uses vertical movements of opening and closing. In addition, it is important to consider that chewing can influence and modulate several other physiological processes related to human nutrition. For example, during mastication the salivary glands are stimulated to produce saliva and enable the formation of the bolus that will then be swallowed. On the other hand, it has been seen that the choice of certain foods to be included in the diet is strongly related to a person's chewing ability or efficiency (Mobley & Dounis, 2013), which will also depend on the state of the teeth (Ellis *et al.*, 2008).

PHASES OF MASTICATION

Different phases are distinguished in the mastication process, where there is a narrow coordination and rhythm among the teeth, masticatory muscles, tongue, lips and cheeks. This coordination of movement depends on a central pattern generator located in the brain stem (Lund & Kolta, 2006). Through the different phases of mastication, it is possible to gain a degree of crushing of the particles that is optimal and that allows the formation of the bolus. Between each of these phases there are predominant movements of the jaw that are then mixed when passing from one stage to the next.

The first "incision phase" begins with the incisors. In this phase a shearing motion is described where the upper incisors work as an upper shear cutter while the lower incisors act as a lower shear cutter. When the incision occurs, at the same time an advancement of the mandible occurs that is usually identified as a preparatory movement. This movement occurs thanks to the contraction of the lateral pterygoid, suprahyoid and digastric muscles, when taking the food towards the mouth. With the help of the tongue, the food is positioned for the cutting movement, making the incision protrusive (simultaneous contraction of the lateral pterygoids) or lateral protrusive (unequal contraction of the pterygoids). The incision of foods and the contraction of the masticatory muscles will depend on the state of the person's teeth and the balance of their occlusion. In the case of more fibrous foods, such as meat, it is necessary to "tear" the food by having the canines apply greater cutting force.

After cutting the foods, next comes the "crushing phase", which occurs in the region of the premolars. In this phase there is a combination of the movements from the previous phase with lateral rotation movements that enable discussion of the posterior teeth finally giving rise to several masticatory strokes or cycles. In this phase the food is prepared to pass to the region of the molars and continue with the "grinding phase". In this last phase the food is reduced to fine particles, finally allowing the formation and swallowing of the bolus.

A current model describes this process as "ingestion", which begins with the selection of a food and ends with its passage through the upper esophageal sphincter during "swallowing". It is considered that ingestion is controlled at three checkpoints, each of which can discontinue ingestion. The first checkpoint is the voluntary selection of food. The second checkpoint consists of the sensory signals of the food, which is obtained after the incisors transport the food to the molars. During this phase, each mouthful is analyzed for taste, retronasal olfaction and oral receptors of the somatosensory system. If this phase is successfully completed, then the food is transformed into a bolus crushing and grinding the foods and the central pattern generators of mastication located in the cerebral cortex and brain stem are activated and the physiological responses needed to prepare the digestion of foods are anticipated. The third checkpoint is swallowing, with the opening of the upper esophageal sphincter (Bourdiol *et al.*, 2020).

COMPLEX MOTOR ACTIVITY

Chewing is based on conditioned reflexes, which are closely related to occlusion, the periodontium, masticatory muscles and TMJs. Chewing is a function guided by basic reflexes such as the jaw opening reflex, the jaw closing reflex and the myotatic (stretch) reflex (Avivi-Arber & Sessle, 2018). The basic pattern of rhythmic movements of the jaw produced during chewing is generated by a neural network located in the brain stem and that is referred to as the masticatory central pattern generator (Morquette *et al.*, 2012). This network is composed mainly of neurons associated with the trigeminal system and is found between the anterior edge of the trigeminal motor nucleus and facial nucleus. Its function is related to the generation of rhythmic patterns as a motor response even in the absence of ascending (peripheral) or descending stimuli. The neurons of the masticatory central pattern generator are subjected to feedback mechanisms that emanate

from various peripheral receptors located in the stomatognathic system and from many central areas such as the cerebral cortex (tonsil, hypothalamus, cerebellum, etc.),thereby causing changes in the motor rhythm of mastication and variability between each masticatory cycle (Aguirre-Siancas, 2017).

JAW MOVEMENT PATTERNS

Jaw movements during chewing are complex and can be described in three spatial planes (frontal, sagittal and horizontal). These movements can be opening or closing, right or left laterality and protrusive or retrusive. It has been shown that the masticatory cycles evaluated through the area have variations during the course of the mastication process, showing a tendency to be of greater amplitude at the beginning of the masticatory process, to then decrease and remain in a "stable" area (Fuentes et al., 2017). As the oral cavity opens wider, the masticatory movements in the horizontal plane are smaller, i.e., the masticatory cycle at the outset should be narrower laterally. However, an analysis with 3D high-resolution images revealed a great variation in amplitude of each masticatory cycle in the three spatial planes (Fig.1).

Chewing patterns can be divided into four types: alternate bilateral chewing, simultaneous bilateral chewing, preferential unilateral chewing and chronic unilateral chewing (Genaro et al., 2009; Brizuela Cordero et al., 2011). It has been described that the most physiological chewing pattern is the alternate bilateral, where the parotic and submaxillary glands are stimulated by the action of the masseter muscles. In addition, in this pattern, support structures of the tooth are stimulated, occlusal stability is promoted, bilateral muscle patterns and dental hygiene is facilitated (Brizuela Cordero et al.). It has been reported that this type of chewing is most frequent in the young adult dentate population (Van der Laan, 1998; Moya et al., 2017). On the other hand, unilateral chewing involves the presence of asymmetries in masticatory dynamics and differences in the load distribution in joints and muscles (Jiménez et al., 2016). In subjects with the loss of posterior teeth, a protrusive masticatory pattern has been described, where foods are crushed with the anterior teeth, due to the absence of the posterior ones.

CHEWING ADAPTATION. Chewing can adapt to several types of changes derived from the environment or the individual. For example, it has been described that the masticatory cycles vary to adapt to the types of foods, that chewing is subjected to a slow reprogramming to adapt to evolutionary conditions such as orthodontic movements, dental wear and tear or aging and that it must also adapt to discontinuities such as tooth loss or prosthodontic occlusal rehabilitation, even dental pain, or mucosa or TMJ pain (Bourdiol et al.).

Type of food

Chewing adapts to the characteristics of the chewed food (Van der Bilt, 1995). The analysis of chewing and its adaptation to different foods has been very complex, since many of its characteristics (for example, texture, flavor, size, shape) can have a simultaneous effect. Consequently, only the mechanical properties of the food have been considered for the analyses described. This is one of the reasons why the hardness of the food has been the most studied characteristic or property (Woda et al., 2006).

To study chewing, different food types have been used for testing, including synthetic foods made from elastomers that allow the physical properties of shape and size to be controlled, but they cannot be ingested (Nicolas et al., 2007). Foods of natural origin have also been used, such as almonds, carrots and peanut, which allows the study subjects to chew more naturally and comfortably (Yoshida et al., 2009). It should also be mentioned that these studies also use cereals like granola (Fueki et al., 2013).

Aging is a dynamic process, where various physiological changes occur; in the oral cavity tooth loss is one of the most common alterations (Saez Carriera et al., 2007). The most popular rehabilitative treatment of people with tooth loss is fully and partially removable prostheses. It has been described that these can modify the chewing process by presenting horizontal and/or vertical oscillating movements during the function, which causes unilateral mastication (Rosado De Oliveira et al., 2005). This modification of the masticatory function leads to a change in the manner of eating, with softer foods being chosen (Bourdiol et al.). Current studies have used peanut as the soft food prototype to analyze the characteristics of chewing, and it has been reported that subjects rehabilitated with implant-supported protheses demonstrate chewing characteristics similar to dentate subjects (Rivera et al., 2020), in addition to the greater force and increased contact area, offering greater comfort and improving the chewing process compared to the conventional prothesis (Ohkubo et al., 2008).

This may be due to the greater retention, support and prosthetic stability in this group (Lauzardo *et al*., 2013). Another food that has been analyzed and its results compared with peanut is cereal-based granola. With a size similar to the peanut, it has been reported that subjects with removable protheses execute wider masticatory movements when chewing granola, and higher values are generally reported for variables such as frequency, speed and area of masticatory cycles compared to the peanut, which is recognized as a food that stimulates chewing and therefore is highly recommended from a mechanical point of view for those subjects who have dental prostheses and who have seen their movements reduced as they lose teeth (Farfán *et al*., 2020).

MASTICATORY CYCLES

Phases: The masticatory cycle is the basic functional unit of chewing and is comprised of three phases: opening, where there is an isotonic contraction of the depressor muscles of the jaw; closing, where the jaw is elevated by action of the elevator muscles; and an occlusal phase, where the contact of the maxillary and mandibular teeth is produced by the isometric contraction of muscles (also described as masticatory stroke) (Brizuela Cordero *et al*.). The opening and closing phases can also be subdivided into slow and fast opening phases and slow and fast closing phases (Cho *et al*.). On the other hand, the mastication sequence can be divided into three stages: early, medium and delayed, in which the characteristics of the masticatory cycles change gradually (Iguchi *et al*.).

Number of masticatory cycles: Masticatory kinematics have been studied in subjects with different characteristics, such as fully dentate individuals, with class I molar or those with dental prostheses, with values being defined between 9 and 24 masticatory cycles and it being necessary to swallow 3.5 g of peanut (Fuentes *et al*., 2017). Other studies describe the number of masticatory strokes as increasing in subjects with dental prostheses, reaching 67 and 90 cycles in subjects with completely removable protheses, between 30 and 104 cycles in subjects with partially removable protheses and between 42 and 114 cycles in subjects with implant-supported protheses, all evaluated under similar conditions (Rivera *et al*.). This increase in the number of masticatory cycles could be because of the low or no peripheral sensitivity that these people have due to the progressive loss of the periodontal mechanoreceptors (Woda *et al*.).

Area of masticatory cycles: In recent decades, it has been possible to accurately determine the area of the masticatory cycles due to technological advances. Previous studies have only been able to describe this area in the frontal and sagittal planes (Gonçalves *et al*., 2014), whereas more recent studies with high-resolution methods and accuracy have enabled the study in the horizontal plane (Fuentes *et al*., 2018a) (Farfán *et al*.). Thus, an average frontal area of 32.46 ± 25.02 mm^2 and a sagittal area of 8.3 ± 7.24 mm^2 has been estimated in subjects with class I normal occlusion (Fuentes *et al*., 2018b). For subjects with removable prostheses, an area in the frontal plane has been described that varies from 39.22 ± 4.07 mm^2 (Rivera *et al*.) to 58.5 ± 32.5 mm^2 (Gonçalves *et al*.) and an area in the sagittal plane that varies from 10.90 ± 5.82 mm2 (Rivera *et al*.) to 12.5 ± 2.5mm^2 (Gonçalves *et al*.). In the case of subjects with skeletal class III, average areas in the frontal plane of 63.5 ± 45.7 mm^2, in the sagittal plane of 19.3 ± 13.4 mm^2 and in the horizontal plane of 20.47 ± 16.68 mm^2 have been described (Fuentes *et al*., 2018a). There is wide variability in the amplitude of the masticatory cycles depending on the condition of the subject; these characteristics must be considered for the comprehensive assessment of chewing and clinical decision-making.

CHEWING ANALYSIS METHODS. Chewing has been evaluated using electromyography, kinematics, force sensors and videos (Nicolas *et al*.; Fuentes *et al*., 2017; Gonçalves *et al*.). Therefore, muscle strength, amplitude and trajectory, time and frequency of mastication cycles can be analyzed.

For the description and analysis of the kinematics of the masticatory cycles, several techniques have been used which offer differing degrees of precision and reliability. The classic studies have described chewing in two dimensions (sagittal and frontal plane) using such techniques as kinesiography (Toman *et al*., 2012), the ARCUSdigma system (Flores-Orozco *et al*., 2016) or the gnathohexograph (Kuninori *et al*., 2014; Yoshida *et al*., 2007). With the development of more modern electronic systems it has been possible to reach new levels of precision and reproducibility. This is the case for electromagnetic articulography (EMA), which is based on the use of alternating magnetic fields to provide information about the position of structures in motion (Joglar *et al*., 2009). The use of EMA has made it possible to revisit aspects of the kinematics of masticatory cycles that had before not been explored

with any amount of accuracy. For example, today it is possible to individualize each masticatory cycle in order to describe and calculate its trajectory, to determine the area that each one occupies in the three spatial planes (frontal, sagittal and horizontal plane) (Fig.1), to measure the mandibular speed in each phase (opening or closing) and to quantify its frequency (Fuentes *et al*., 2017).

In terms of the morphology of the masticatory cycles, studies that use more modern techniques have corroborated the previous observations made with less accurate technologies, for example, that the cycles are elliptical with a great variation regarding amplitude, area, direction, inclination and side of preference in the frontal plane. Nevertheless, thanks to the studies conducted with EMA in 3D, today it is possible to also state that in the frontal plane cycles with a figure "8", with great irregularity in their trajectory and an inclination that can be vertical, horizontal or close to 45º are described (Fig.1) (Fuentes *et al*., 2017).

It is now possible to study both the individualized cycles as well as the entire masticatory process in 3D, and concentric movements can even be differentiated from those eccentric ones made with the jaw (Fig. 2).

MASTICATORY PERFORMANCE AND EFFICIENCY. At the same time in which modern oral rehabilitation procedures have been developed, different methods have been proposed to measure or quantify masticatory function. In the beginning these methods lacked standardization and there was no consensus about which technique was best or what the test foods should be to assess mastication. However, the first reports agree in that the uses of natural food that is
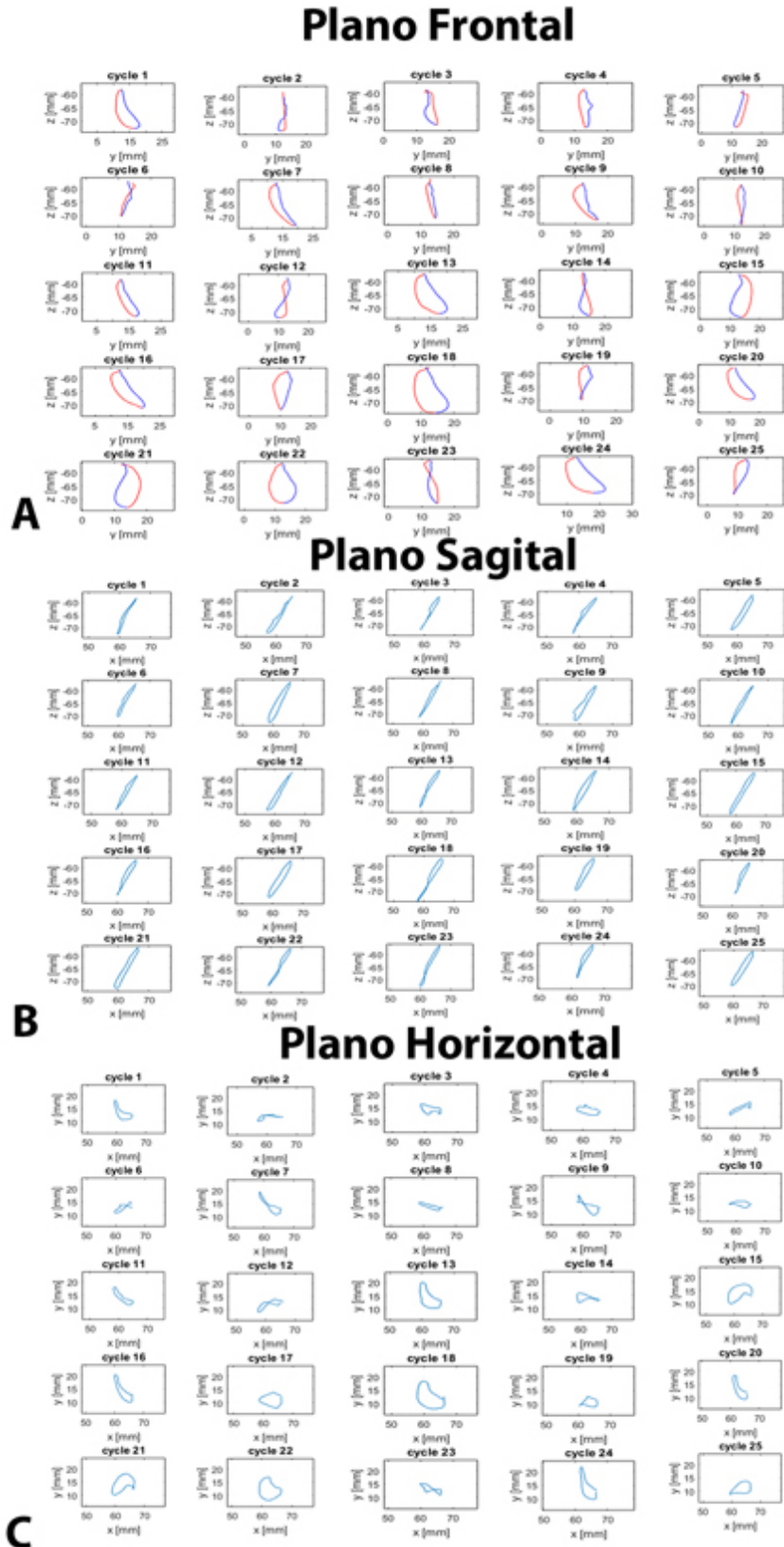

Fig. 1. Individualization of masticatory cycles through 3D electromagnetic articulography in:A: frontal plane, B:Sagittal plane, C:Horizontal plane.
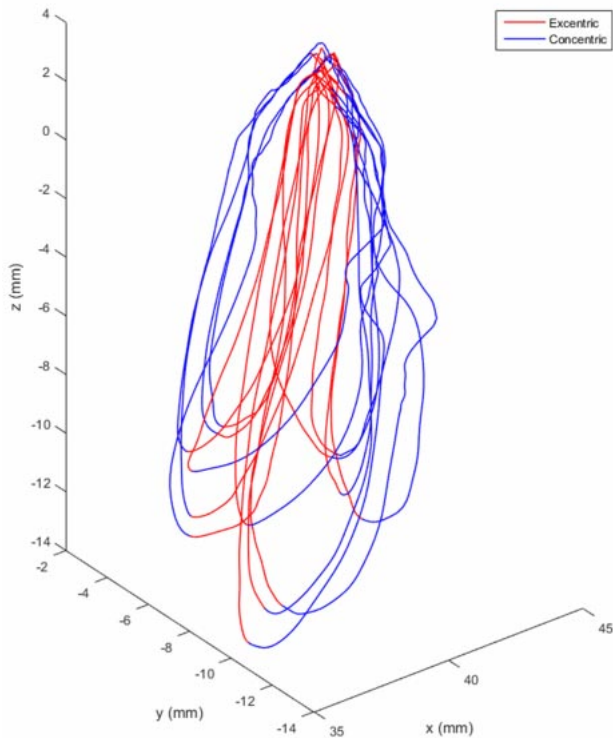
Fig. 2. Masticatory cycles observed on the x-, y, and z-axis, where the concentric (blue) and the eccentric (red) mandibular movement is differentiated.

usually consumed should be preferred, with peanut and its derivatives being a recurrent test food (Manly & Bradley, 1950). Nowadays, a classic and widely used method for the evaluation of masticatory function is the determination of masticatory performance and efficiency proposed by Manly & Bradley in 1950. According to that study, a person's masticatory performance can be calculated based on the percentage of peanut chewed which can pass through a sieve of a certain diameter (as a way to measure the degree of crushing of a food) executing a certain number of masticatory strokes or cycles (usually 20 masticatory strokes). In addition, masticatory efficiency can be calculated from the number of masticatory strokes or cycles required to obtain a certain level of pulverization of a food that is generally peanut (Manly & Bradley). In this study it was determined that the masticatory performance of healthy subjects with complete natural teeth is 88%, whereas efficiency is a parameter that varies substantially according to the number of teeth present (Manly & Bradley).

Tooth loss and the consequent reduction in occlusal contacts is directly associated with a reduction in masticatory performance, mainly in older adults (Ikebe *et al*., 2012; Naka *et al*., 2014). Also, several exploratory population studies have found that people with better dentition and masticatory function report a significantly greater consumption of foods and ingestion of nutrients than those people with a reduced state of oral health (Tada & Miura, 2014). A long tradition of published studies going back more than half a century has already indicated that masticatory performance is a determining factor for people when choosing what type of food to eat, seriously affecting nutrition, mainly of older adults (Buschang *et al*., 1997). More recent studies have investigated this aspect, finding that the state of dentition and the number of teeth present could influence food selection according to its texture (Ellis *et al*.), affecting the appropriate ingestion of certain foods such as fruits and vegetables (N'gom & Woda, 2002).

On the other hand, tooth loss and the ensuing deterioration of the masticatory function have been negatively associated with the perception of oral health-related quality of life (Batista *et al*., 2014; Gerritsen *et al*., 2010) and with a greater incidence of symptoms of depression (Laudisio *et al*., 2014).

CHEWING AND COGNITIVE FUNCTION

In the last few years it has been seen that chewing not only fulfills a role in the processes of food ingestion and nutrition, but it is also able to influence the development of neurodegenerative diseases. One of the most relevant findings about chewing is that the cognitive function dependent on hippocampal activity may be closely related to masticatory function (Chen *et al*., 2015). This relation has begun to be studied more thoroughly since observational studies conducted on various adult populations have shown that low masticatory ability is associated with cognitive deterioration or dementia (Kim *et al*., 2017). Recent studies conducted on animal models have demonstrated that a reduction in masticatory activity results in a deterioration of spatial memory and learning function (Fukushima-Nakayama *et al*., 2017). In addition, studies on healthy subjects have shown that chewing can induce an activation of the right premotor cortex, precuneus, thalamus, hippocampus and inferior parietal lobe, which suggests its relation with positive effects on the memory (Hirano *et al*., 2008). The activation of different areas of the cerebral cortexresulting from chewing had already been previously proposed in studies where the mastication of chewing gum

demonstrated an increase in regional blood flow of the brain in areas such as the primary sensorimotor area, complementary motor areas, insula, cerebellum and corpus striatum (Momose *et al.*, 1997). Given that a deterioration in masticatory function is dependent on the presence of teeth, current studies suggest that the process of peripheral deafferentation in the stomatognathic system could project globally in the central nervous system and become a critical factor that could trigger and/or aggravate neurodegenerative diseases (Jou, 2018). A recent qualitative systematic review indicates that masticatory function can act as a protective factor in subjects with cognitive decline and neurodegenerative diseases by increasing cerebral blood flow. This may also be influenced by the intensity of the masticatory function and the number of functional teeth in the mouth (Chuhuaicura *et al.*, 2019). Similarly, a greater number of residual teeth in an older adult also has been associated with a lower risk of suffering dementia later in life (Oh *et al.*, 2018).

CHEWING AND QUALITY OF LIFE. Over time it has been possible to relate the increase in masticatory capacity with the increase in people's quality of life (Baba *et al.*, 2009). Other factors, low education, being single and socioeconomic level have also been shown to reduce masticatory capacity in relation to the difficulty of chewing hard foods (Milagres *et al.*, 2018). In relation to the number of teeth, completely edentulous subjects may not have seen an improvement in their quality of life after being treated with fully removable protheses (Alves *et al.*, 2018), but there has been an increase associated with quality of life with the use of implants due to an increase masticatory efficiency and comfort (Sun *et al.*, 2014).

CONCLUSION

Recent studies have offered a new vision of the mechanics of mastication and its impact on various processes such as nutrition or the development of neurodegenerative diseases. Thus, any modification in the state of dental health, salivary flow or neuromuscular apparatus can affect it.

It is necessary to stimulate chewing and for this purpose the choice of foods should consider the oral health status and chewing characteristics of each person. Therefore, it would be advisable for dentists to be integrated into the multidisciplinary nutrition team.

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RESUMEN: La masticación es el primer paso en el proceso de digestión en los mamíferos, es un proceso altamente coordinado y con una compleja actividad sensoriomotora, cuyo objetivo es preparar los alimentos para la formación del bolo alimenticio y luego la deglución, es un proceso con etapas definidas y patrones de movimiento que se adaptan a los cambios derivados del entorno o del individuo, aquí se revisan las principales características de la masticación, incluyendo aspectos de la fisiología y características de la mecánica del movimiento mandibular, se destacan los últimos avances reportados y las nuevas metodologías utilizado para un análisis de la masticación, lo que ha permitido recolectar datos más precisos y confiables, así, veremos cómo las nuevas tecnologías han permitido comprender mejor esta función y su relación con aspectos de la salud general de un individuo como la nutrición o la aparición de enfermedades neurodegenerativas; además, en esta revisión destacamos la estrecha relación que existe entre la masticación y la calidad de vida.

PALABRAS CLAVE: masticación, ciclos de masticación, movimiento mandibular, nutrición, enfermedades neurodegenerativas, calidad de vida.

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