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An update about artificial mastication

Marie-Agnès Peyron^{1,2} and Alain Woda^{3,4}

Developing masticatory apparatus, chewing robots or an artificial mouth is an old but ever more important goal in food science, nutrition or dental research fields, as reflected by the number of existing digital or biomechanical systems. Whatever the objective of the approach, basic knowledge of the physiology of mastication, adaptation and neurophysiological control is absolutely needed before conceiving an apparatus. Obviously, the final step in the development of a mastication simulator is its validation before performing food or food bolus characterization. This validation step is imperative to avoid biased interpretation and can be performed through *in vivo*–*in vitro* comparison of particle size distributions in food boluses obtained after normal mastication. This kind of validated machine offers the chance to produce boluses for other related uses such as nutrient bioaccessibility or digestion studies, for example. Such an apparatus can also be employed to simulate different dental states or ageing conditions.

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Introduction

Two main driving-objectives can be identified while simulating mastication: firstly, when the goal is to improve knowledge, to reproduce the biomechanical aspects of the masticatory system or to analyze the effect of forces, movements or constraints, for example. It generally results in the development and the use of mathematical models alone in an *in silico* approach or associated with mechatronic techniques to develop robots

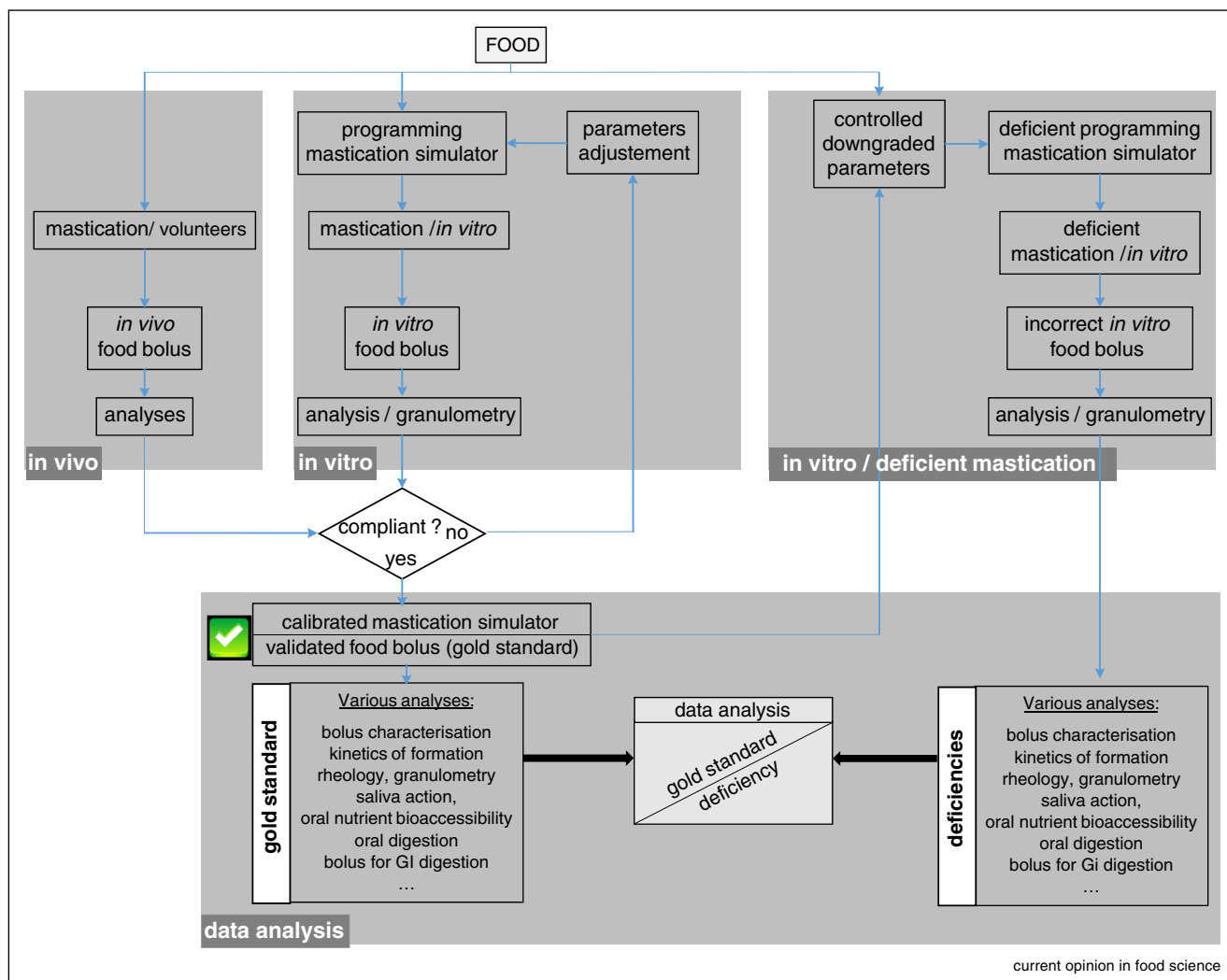
for biomechanical studies. Secondly, in very different approaches, simulators can be used to study either food bolus characteristics or to produce boluses for subsequent analyses (Figure 1).

Despite the important understanding gathered in several aspects of the masticatory process, simulation of mastication in the area of food science has, too often, been over-simplified and reduced to grinding, probably due to the lack of knowledge of physiology. This review resumes the main physiological key points of masticatory process, and describes the different existing simulations with biomechanical and modalities of functioning.

Mastication must be understood before being simulated

Through a complex and well-coordinated sensory-motor and visceral activities, mastication of a solid mouthful results in a bolus made of particles reduced in size, moistened enough to be cohesive, plastic to avoid particle aspiration, and to permit passage through the throat without discomfort or pain. The sensory-motor and visceral program is continually commanded by the central nervous system. The food properties are sensed as early as the first bite and, through sensory-motor feedback, the masticatory program is adjusted to the changes in bolus features occurring along the masticatory process. This highly complex and feedback-dependent dynamic complicates any attempt to reproduce instrumentally mastication. Therefore, advanced knowledge about how food structure influences the pattern of oral processing is required. Food is a complex stimulus, but the physical dimensions modulating the oral processing are limited to its hardness, its rough rheological dimensions (plasticity, elasticity or brittle nature for example), and size of the mouthful. Briefly, an increase in food hardness as well as in mouthful size leads to an increase in the number of masticatory cycles (tooth strokes) and applied muscle forces, whatever the rheological nature of the food. On the other hand, the rheological properties of food seem mostly to impact the kinematics of mandibular movements due to a need to adjust the combination of compression and shear stresses [1]. Furthermore, fracture propagation during mastication inside the food matrix strongly depends on its structure [2]. The number of fractures and consequently of food fragments seems mainly to depend on food toughness [3] with resistant food often favouring fracture propagation, resulting in greater comminution. In parallel, the many and well-documented individual chewing strategies

Figure 1



Flowchart displaying the key steps in development through sequential *in vivo*-*in vitro* actions, and validation stage of a mastication simulator before operating it to produce boluses for multiple purposes.

help to accomplish the mechanical food disruption. The end point of the masticatory sequence is determined by the intrinsic properties of the bolus. Thus, swallowing is initiated when the bolus has been perceived by the oral receptors to be ready for safe-swallowing. Thus the swallowing threshold is a combination of numerous physical dimensions including particle size, cohesiveness, elasticity, plasticity, moistening, intrinsic action of mucines and enzymes, among other factors. In particular, particles must be bound together by viscous forces rendering the bolus sufficiently cohesive [4,5]. This swallowing threshold is specific to each food.

In summary, the basic points to be considered, before simulation and according to the research strategy, are [1^o,2,5]:

- 1) Mastication of solid food ends with a bolus swallowable without risk of mucosal injury and aspiration. For each food, a correct and specific granulometry, rheology and saliva impregnation characterize a swallowable bolus. In normal mastication, bolus particle size distribution is specific to food structure and similar between boluses from different subjects.
- 2) If such a bolus cannot be produced, mastication must be considered as impaired. At the individual level, two indicators sign for an impaired mastication: increased bolus granulometry above a certain threshold level and variation in frequency of the strokes while masticating a given food compared with normal mastication.
- 3) In subjects with perfectly healthy mastication, increasing either the force or the number of tooth strokes or the combination of compressing *versus*

shearing constraints allow adapting to different food structures or to harder or more difficult food stuffs to chew.

- 4) Subjects with moderate impairment of the anatomical or physiological conditions of the masticatory apparatus can also succeed in making a viable bolus through a more demanding adaptation. Again, the adaptation relies on increasing the force, the number of tooth strokes or the constraint modes.

Different kinds of simulation/reproduction of masticatory function

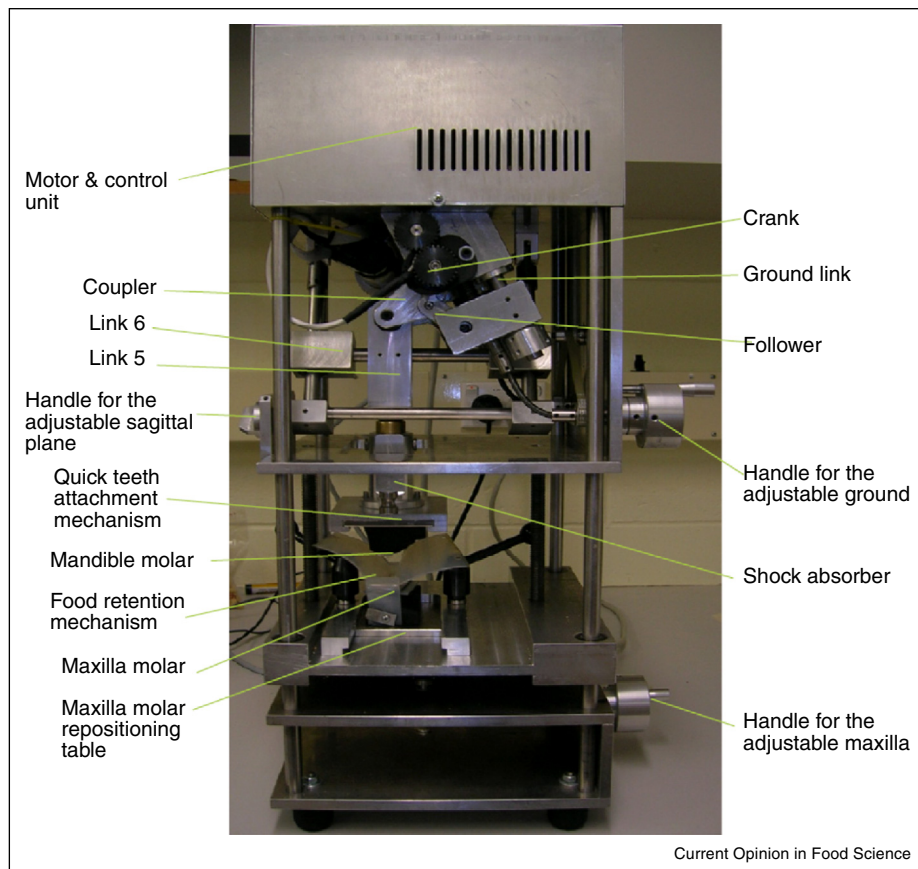
Biomechanical knowledge-oriented simulation

Computer or computer-assisted models have often been elaborated to analyze the dynamics of biomechanical aspects of the masticatory function for dental, medical and therapeutic objectives and for understanding biological systems. It participates in predicting jaw movements, muscle activations, recruitment patterns and controls, resulting forces, or movements at the temporomandibular joint [6–12]. Recently, some digital investigations based on the discrete element method were conducted on the food breakdown pathways during oral processing and the

establishment of links between food fragmentation and initial food structure [13].

Several mastication robots or mechatronic devices have been conceived and designed to study biomechanics of the masticatory process. Development of a series of mastication robots was carried out for quantitative and dynamic assessment of mechanical stress applied to oral elements during oral activity. The ‘Waseda Jaw (WJ)’ systems were mostly developed to analyze the mechanical effects of mastication on jaw bones in terms of position, force, velocities and muscle controls [14,15]. A second example of a mechatronic chewing device is of particular relevance since it can reproduce the entire suite of complex functions and movements involved during mastication, encompassing most of oral applications [16,17]. The main objective of this device was to propose a ‘chewing robot’ (Figure 2a) able to reproduce a molar trajectory in actual dimensions [18,19,20]. Aside from the area of food science, dentistry and specialists in dental materials developed tools to evaluate fatigue, resistance, wear or behaviour of restorative pieces under mechanical testing as close as possible to *in vivo* oral conditions [21–23].

Figure 2



The ‘chewing robot’.
Reproduced with authorization from [30].

Food-oriented or bolus-oriented simulation

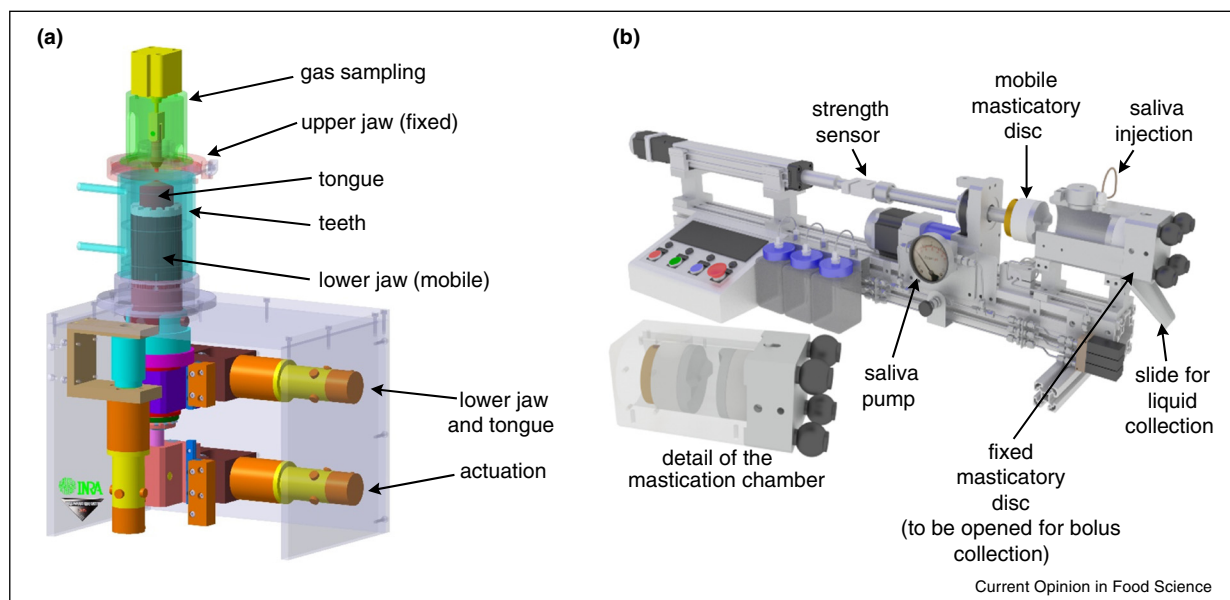
The first attempts to mimic jaw movement with a main interest towards the food sample were equipment roughly designed to activate the upper jaw against the food sample for measuring mechanical properties of food texture or equipped for example with a piston presenting a cuspal angulation reflecting angles observed in the mouth [24,25]. This kind of machine, considered as providing objective methods for food evaluation, generally displayed significant correlation between sensory perception and mechanical measurement. Similarly, food science researchers tried to improve the first basic devices developed to describe food texture [26]. For example, the experimental ‘crush chamber’ was designed to include evaluation of acoustic, tactile and olfactory stimuli during crispbread mastication [27]; the ‘BITE Master II’ was elaborated to study the perception of cheese hardness during the very first chew [28], and an ‘*in vitro* mouth model’ was developed for the determination of salt release from the food matrix [29]. The ‘chewing robot’ (Figure 2a) was first developed to reproduce the mechanics of the chewing process but could also be proposed in the future to give a quantitative analysis of mechanical disruption allowing texture analysis of a food sample in nutritional questionings [30]. In addition, some simple instrumentation was developed for semi-solid food issues [31].

Since it leads to perception of flavour, the release of volatile aromatic compounds during food disruption is one of the issues most studied using chewing simulation [32–37]. In these different approaches, the liberation or retention of volatile molecules was measured in relation to the presence

of saliva of known flow and composition. These needs induced specific requirements that were very challenging for the conception of a masticatory device. It led to debatable choices; for example, in terms of food disruption modalities, the volume of the artificial mouth, or the duration of masticatory sequence, to name a few. The ‘artificial mouth’ developed by Salles and collaborators (Figure 2b) is probably the most successful apparatus for measuring aroma release during chewing since it encompasses more physiological purposes than others [36,38]. The apparatus produces food breakdown due to two opposite tooth arches actuated in both vertical and horizontal/angular motions. Volatile retention is completed with a gas introduced into the system, allowing air sampling in synchronization with mastication events, as sniffing does *in vivo*. Food breakdown has only been ‘validated’ against peanut particle size observed *in vivo* in a very few number of subjects [36].

The ‘AM² apparatus’ (Figure 3b) is the unique mastication machine focusing on the food bolus as the result of mastication while introducing most of the actual biomechanical masticatory features [39,40]. The AM² apparatus thus permits simulation of mastication in various oral contexts and provides a complete food bolus recovery after mastication for further analysis. It produces a food bolus with properties similar to those of a bolus produced by *in vivo* mastication in numerous subjects ([41] — Figure 1). This kind of device can also be successively employed to investigate food science, physiological or nutrition fields such as nutrient bioaccessibility assessment or digestive process follow-up in link with oral food transformation ([42] — Figure 1).

Figure 3



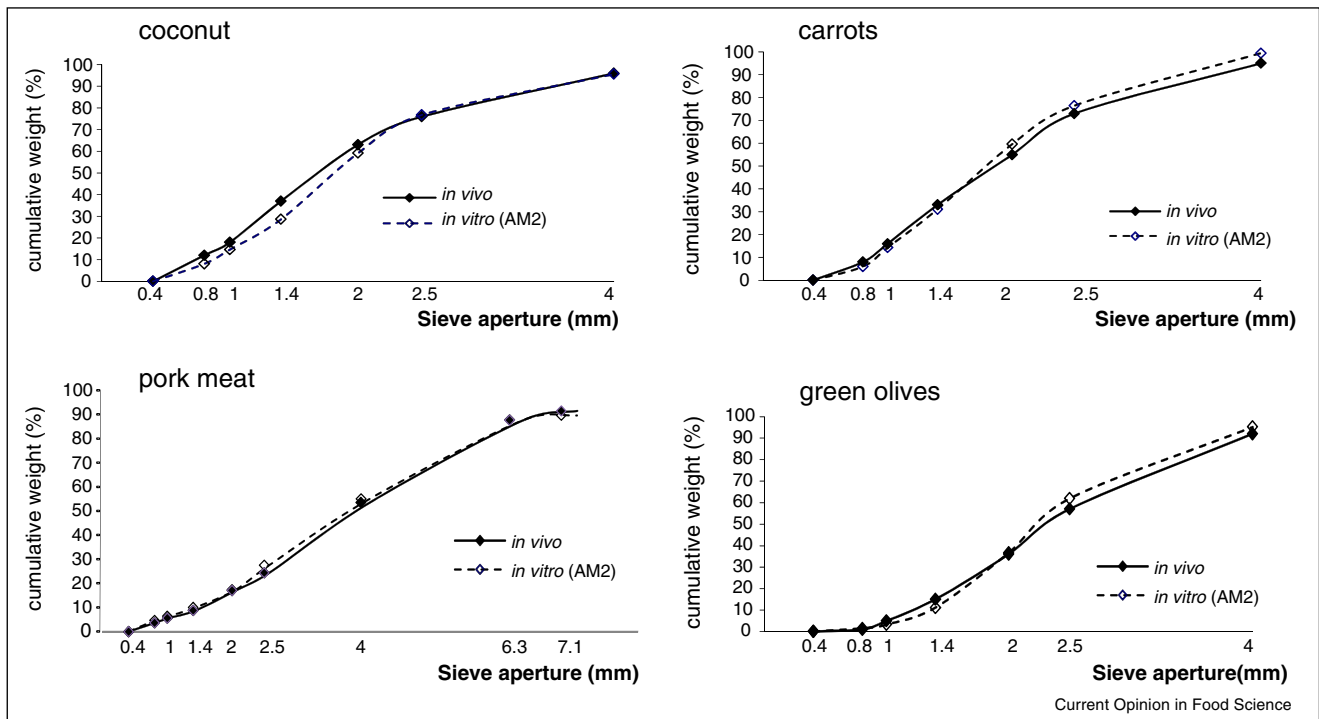
(a) The ‘artificial mouth’ (reproduced with authorization from [36]), and (b) the ‘AM² masticator apparatus’ [39].

Biomechanical aspects of masticatory simulators

Depending on the reason for using them, the various existing mastication simulators have differently set five key variables: teeth or equivalent, inside-mouth volume, saliva or equivalent, temperature control, and kinetic and stress modalities of functioning. The most crude simulation of tooth function is probably Mills's 'in vitro mouth model' that only compresses a food sample under a flat piston to measure the salt released in the liquid medium [29]. Other developers equipped their apparatus with teeth using either a complete human skull ('Waseda Jaw', [14]), patient's complete arcades ('Bite MASTER II', [28]), or series of molar teeth fixed on two opposite ring-shaped cylinder 'artificial mouth', [36]). The major limit of this type of choice is that it under-estimates the role of the central nervous system in taking advantage of the complex anatomy of the tooth arches. The control of masticatory movements and forces performed by the nervous system cannot be replaced and this renders difficult the interpretation of what happens to the food sample in term of mechanical stress and strain. The experimental mouth proposed by Salles *et al.*, with teeth organized on a circle-shaped design (Figure 3a), mimics the normal human tooth contacts and offers more contacts between teeth and food than in a human mouth, making the estimation of the forces and constraints

applied to the food samples difficult. It also renders difficult the recovery of the food particles that constitute the bolus. Consequently, it could probably not be used for other purposes than study of the dynamic release of volatiles during mastication. Finally, the use of dental arcades similar to the 'real' anatomy has not been shown to give better correlation between sensory and instrumental hardness assessment than when food hardness is measured by a classical compression test. It may also introduce another source of variation by its inability to maintain the food particles between the teeth. This limit was accounted for in the artificial mouth of Salles's team by a tongue placed at the centre of the ring supporting the teeth, programmed to place food particles on the teeth. This design, however, does not gather food particles in a bolus since particles are inevitably distributed over the full ring [36]. Despite these limits, this latter device seems to be the most advanced for the study of aroma release during oral food breakdown. The systems equipped with cutting blades [37] or triangular-shaped elevations [27], cannot be considered to mimic masticatory action due to the absence of a lot of components of movement, of 'tooth' elements and no control of the stress applied to the food sample. In the AM² apparatus, tooth function is reproduced but not tooth anatomy. Tooth action is made by two opposite triangular forms whose active surfaces are similar to the sum of the molar and

Figure 4



Comparison of particle size distributions obtained in food boluses collected at the end of mastication *in vivo* in volunteers with normal dentitions or *in vitro* with the AM² masticatory apparatus.

premolar surface areas involved when chewing a standard bolus. These ‘tooth’ elements are actuated by translation and rotational movements to ensure correct impact on food and gathering of the particles before tooth confrontation [39].

Three other key points are important in the development of a simulator. Saliva should be used. Ideally, its composition, flow distribution along masticatory sequence and total injected volume should mimic those seen in the human mouth. The volume of the ‘masticatory chamber’ should be similar to the volume of the mouth and a possibility of controlling the oral temperature should exist. Saliva, volume and temperature items are fundamental for studying aroma or nutrient release and food texture measurements. Not all apparatuses are equipped for these controls and this may affect data interpretation.

The final items that should be considered are kinetic factors and constraint modalities of functioning. Various degrees of freedom have been chosen depending on the main purpose for using the apparatus (aroma release, food texture/bolus measurements, dental training, for example). Obviously, complex mandibular movements adjusted to the food being chewed cannot be completely reproduced. Complete feedback control is always absent although it has been sought while studying the first stroke [28]. This requirement has been addressed differently by choosing to reproduce or control the mechanical function, jaw movements, imitation tooth anatomy and applied forces [30,36,39], or by applying fracture propagation knowledge to food matrix during disruption (tooth action in mechanical terms) in order to select appropriate stress-strain conditions [39].

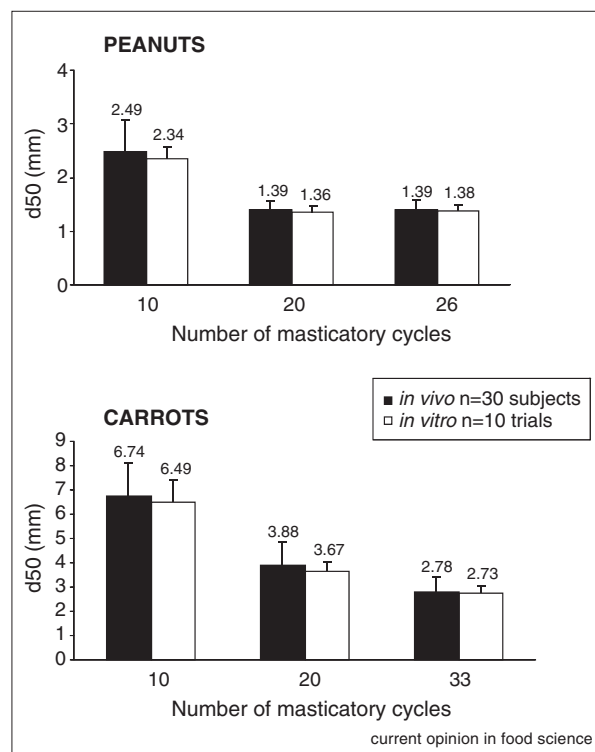
Validation of mastication devices by food bolus analysis

The food bolus is the main focus of interest in most topics in food science research. Food bolus analysis is at the crossroads between food structure, food formulation, food perception, food oral processing and the further stages of digestion. The ready-to-swallow bolus contains information about the oral conditions of its formation. In addition, it constitutes the vector for nutrients. For all these reasons, a mastication simulator provides a valuable contribution since it allows recovering the totality of the food bolus at the end of the masticatory sequence. During mastication, food sample is drastically disrupted to form a cohesive entity, which can be swallowed easily and without risk of particle aspiration. As particles are formed, they are mixed with saliva. During this process, the smaller the food particles, the greater the surface contacts between food and saliva, favouring the access of salivary enzymes to substrates. The ready-to-swallow final bolus is composed of particles of various sizes and saliva or juice

released from the food matrix. The bolus can be analyzed for particle size distribution, a major characteristic of food disruption.

Any chewing device used to provide food boluses has to be validated against human mastication (Figure 4). Such validation has not been conducted for many of the proposed systems. This deficiency is striking in digestion studies, which are generally operated without a specific masticatory apparatus or with food particles coarsely ground or minced and mixed with saliva or enzyme during an uncontrolled or unjustified time, to obtain what must be considered as a fortuitous food bolus [43]. Mishellany-Dutour *et al.* [41] validated the AM² apparatus by comparing particle size distribution and median particle size of an *in vitro* bolus with a bolus made *in vivo* by selected subjects with normal dentitions, a correct occlusion and a normal saliva flow (Figures 4 and 5). Some bolus rheological properties, hardness or cohesiveness, for example, are also very informative of the suitability of the bolus to be safely swallowed [5] and should also be used for *in vivo/in vitro* validation purposes.

Figure 5



Median particle size (d50 values) of food boluses collected after 10 cycles, 20 cycles of at the end of the masticatory sequence, *in vivo* in volunteers with normal dentitions and *in vitro* with the AM² masticator apparatus. Reproduced with authorization from [40].

Conclusion

In summary, when the major objective of simulation is to reproduce the biomechanics of jaw movements and forces, mathematical models or robots are more appropriate. When the objective is to study the resulting food bolus, a device reproducing masticatory parameters and correct food disruption is a better option. The specifications and technical limits for a simulation device depend on the primary research purpose: aroma release, food texture assessment, production of a food bolus providing for subsequent digestion analyses, the impact of a change in food formulation on bolus, biomechanical analysis of stress applied to oral elements and other factors are specific questions. Nevertheless, taking account of the main laws governing the biomechanical mechanisms of the masticatory processes and the dynamics of bolus properties are always needed [26]. Knowing the features associated with a correct use of an *in vivo* bolus simulator allows the preparation of a realistic bolus for subsequent analyses (Figure 1). In addition, it favours interpretation of the results. Obviously, all apparatuses must be validated before use and this essential step can only be done by comparing boluses obtained *in vivo* in a sufficient number of individuals *versus* boluses obtained *in vitro*. Clearly, a mastication simulator cannot reproduce the large range of mastication strategies observable in human. The apparatus is therefore assumed to reflect average mastication. A well-designed apparatus can be employed to investigate the kinetics of bolus formation in terms of particle size, rheological behaviour, saliva impregnation, compound release or biochemical modification, as a function of food structure, food formulation and processing, or even to simulate several dental or ageing conditions (Figure 1). Mimicking oral steps using a kitchen food processor or a static oral digestion apparatus, as is too often done in digestion studies, cannot produce a realistic bolus for a majority of solid foods, especially if considering specific populations such as the elderly or infants, because it cannot produce a particle size distribution and cannot reproduce the dynamics of bolus formation. If these complex oral steps are overlooked, data obtained from bolus analyses in digestion studies or for texture assessment during the whole masticatory sequence could be biased.

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