Hindawi
Journal of Food Quality
Volume 2022, Article ID 9176628, 12 pages
https://doi.org/10.1155/2022/9176628

Research Article

Application of Food Mechanics and Oral Processing in Modelling First Bite of Grilled Meat

Ilija V. Djekic,[1] **Jovan G. Ilic**,[1] **Bartosz G. Sołowiej**,[2] **Rastko I. Djekić**,[3] **and Igor B. Tomasevic**[1]

[1]*Faculty of Agriculture, University of Belgrade, Zemun, Belgrade 11080, Serbia*
[2]*Faculty of Food Sciences and Biotechnology, University of Life Sciences in Lublin, Lublin 20-033, Poland*
[3]*Faculty of Mechanical Engineering, University of Belgrade, Belgrade, Serbia*

Correspondence should be addressed to Ilija V. Djekic; idjekic@agrif.bg.ac.rs

Received 4 August 2022; Revised 30 September 2022; Accepted 15 October 2022; Published 21 October 2022

Academic Editor: Slim Smaoui

This study analyzed the potential of modelling meat mastication by using pork and poultry meat as food with different physical properties under different grilling temperatures. For the purpose of modelling oral processing, temporal dominance of sensations and finite element methods were employed. A panel with ten subjects was trained and used for oral processing analysis and temporal dominance of sensations revealing in-mouth sensations and mastication characteristics. In parallel, the second aim was to evaluate the mechanical properties of the samples and explore the potential of simulating the first bite using the finite element method. Based on the textural parameters, a 3D model of grilled meat was created and a first-bite simulation was performed. A higher level of differences was observed comparing the number of chews for pork meat compared to poultry meat. The chewing rate showed a statistical difference with values in the range of 1.31 chews/s to 1.46 chews/s for pork meat and between 1.36 chews/s and 1.42 chews/s for poultry meat. Firmness was the predominant sensory attribute recognized by panelists at the beginning of mastication, which confirmed our approach used for first-bite modelling. Simulation results show the growth of internal stress following the jaw's path. Presented models demonstrate that the highest values are around teeth pressure and lead to a conclusion that upon biting, the meat structure will suffer irreversible damage dividing the grilled meat into two pieces, as it happens during the first bite. The main conclusion of this study is that by combining results from oral processing and testing of mechanical properties of the grilled products, it is possible to simulate the first bite.

1. Introduction

Analysis of different structural changes, including in-mouth sensations that occur during mastication, is referred to as oral processing [1]. The complexity of understanding food oral processing consists of three types of evaluations, depending on the time the measurements occur, namely: (i) *ex ante*, (ii) ongoing, and (iii) *ex post*. *Ex ante* analyses mainly target different physical and mechanical properties measured prior to mastication that can help in understanding deformations and fracturing of food that occur in the mouth from the first bite until swallowing and may support explaining eating and sensory perception [2]. The majority of ongoing studies that analyze oral processing during mastication confirm that basic characteristics such as the number of chews, bite size, consumption time, and eating rate are correlated with food characteristics [3–5]. In parallel, the use of temporal dominance of sensation (TDS) helps in understating in-mouth sensation changes [6]. This sensory tool is capable of screening sensations associated with textural and flavor attributes that occur during mastication from the first bite to swallowing [7]. Food structural changes, particle size distribution, and saliva incorporation also help in understanding the structural behavior of food [7–9]. Finally, *ex post* studies focus on bolus characteristics, swallowing, and effects of food consumption such as energy and nutrient intake [10] and satiety [11]. The majority of these methods are used in terms of interpreting certain oral processing phenomena, rather than in modelling certain mastication activities.

The finite element method (FEM) is an engineering tool that found its application in food science focusing on mechanical properties and predicting the behavior of materials, such as in the work of Celik et al. [12] for the purpose of simulating dropping of apples, Yousefi et al. [13] for drop testing of pears, Haiyan et al. [14] for dropping eggs, or Guessasma et al. [15] for simulating the behavior of starch/protein composite. All these studies used FEM to determine the deformation behavior of food [13]. When it comes to mastication, FEM was used in analyzing stress and loading on teeth [16], occlusal static and dynamic loading during biting or chewing [17], or analyzing simulating mastication associated with different materials used as substitutes for molars [18]. However, all these studies used FEM from a dental rather than a food science perspective. In meat science, the use of FEM supported by mechanical properties is not new but was mostly associated with mass/heat transfer in terms of cooling and/or heating [19–24]. However, there were no studies that simulated the first bite of grilled meat using FEM.

Regarding culinary methods associated with meat, the two basic methods are cooking and grilling [9] with sous-vide [25] and ohmic heating [26] promoted as new promising techniques. Meat that is used as food is a postmortem skeletal muscle tissue of animals [27] as it undergoes a variety of physiological and biochemical changes after slaughtering [28]. The composition of meat depends on numerous characteristics such as species/breeds, age, and also the muscle position in the carcass [29], where the complex structure of meat comprises fibers, intramuscular connective tissue, and intramuscular fat [30]. The complexity of biological materials influences mechanical properties and, as such, cannot be easily explained like in the case of less complex materials such as metals and alloys [31]. When it comes to solid food, there is a certain barrier in connecting the field of material sciences with biological sciences [32], mainly due to the matrix of food tissues and certain limitations in using mechanical tests per se ignoring a wider (food science) perspective. In that sense, meat is considered one of the most complex types of food with interacting components operating at the microscale [33]. Therefore, modelling meat as a material and meat consumption as a process is considered a scientific challenge.

This paper had two main objectives. The first was to characterize sensory and oral processing characteristics of pork and poultry meat as food with different physical properties under different grilling temperatures grilled at three temperatures and identify parameters of interest for simulating mastication from the first bite. The second aim was to evaluate the mechanical properties of the samples and explore the potential of simulating the first bite using the finite element method.

2. Materials and Methods

2.1. Pork and Poultry Meat. Pork (*m. longissimus dorsi*) and poultry (*m. pectoralis major*) meat was purchased locally from a butcher store in Belgrade, Serbia. After purchasing, meat was cut into uniform pieces of 200 gr (pork) and 100 gr (poultry), vacuumed, and stored in the refrigerator at 4°C. Before grilling, meat was placed at room temperature for half an hour.

2.2. Cooking Loss. Prepared uniform pieces of meat were grilled using a Tefal grill (OptiGrill+) on three defined grilling regimes (T_1 is the shortest grilling time; T_2 is the medium grilling time; and T_3 is the longest grilling time) in accordance with the instrument's manual for pork and poultry meat (time duration between four and seven minutes). Grilling temperatures on the surfaces show a range between 263.47°C and 272.1°C for pork meat and 238.42°C and 249.24°C for poultry meat, with medium grilling time having the lowest temperature. The achieved thermal temperature in the center of the product was from 67.17°C to 90.63°C (pork) and 78.77°C to 99.3°C (poultry), confirming its safe consumption.

The indicator consists of a sensor measuring the grilling meat thickness, based on which the instrument indicates the doneness level by changing the LED bulb light color. To control the process, temperatures in the samples' center during grilling were measured with a digital thermometer (Trotec GmbH - Model BT20, Germany), while the temperature of the grilling surface was measured using an infrared thermometer (TES-1327KUSB) (Table 1). Grilled samples were settled to rest at room temperature and then sealed in vacuum bags and stored in the refrigerator at 4°C.

The weight of the samples before and after grilling was measured using an analytic balance (OHAUS Adventurer-Model AR2140, USA), and the cooking loss was calculated by measuring the weight differences [25].

2.3. Density. Upon grilling, density was measured by determining the sample mass and volume [34] and measuring the external dimensions (length, width, and thickness). Grilled samples were cut into cubical samples ($20 \times 20 \times 20$ mm) using a thin-bladed sharp knife. Assuming a constant cubic shape, based on 30 replicates, for both types of meat and three grilling temperatures, density was calculated as shown in Table 2. Dimensions of the samples were measured with a digital vernier caliper while mass was measured using an analytical balance (OHAUS Adventurer-Model AR2140, USA).

2.4. Sensory and Oral Processing Evaluation. The panel consisted of 10 panelists experienced in both sensory and oral processing evaluation participating in the study. All panelists were in good general health condition, with no reported dental problems and with a normal range for BMI of 18-25 kg/m^2, as suggested by Forde et al. [35]. All panelists are well-trained, have already participated in sensory and oral processing studies associated with animal-origin food, and have passed basic tests for taste, odor, and texture in line with ISO 8586 [36]. Two training sessions (duration 2 hours each) were performed for sensory evaluation, while for oral

Table 1: Summary of the heating parameters for samples prepared using three grilling working regimes.

	Pork meat			Poultry meat		
	T_1	T_2	T_3	T_1	T_2	T_3
Grill temperature [°C]	269.04 ± 7.64	263.47 ± 7.66	272.1 ± 7.93	244.08 ± 6.47	238.42 ± 12.67	249.24 ± 6.48
Temperature in center of product [°C]	67.17 ± 3.15	74.57 ± 3.41	90.63 ± 1.95	78.77 ± 0.65	94.43 ± 0.83	99.30 ± 2.03

Legend: T_1 is the shortest grilling time; T_2 is medium grilling time; T_3 is the longest grilling time. Testing was performed in three replicates.

Table 2: Summary of the oral processing behavior parameters for pork meat samples prepared using three grilling working regimes.

	Pork meat		
	T_1	T_2	T_3
Density [g/cm^3]	1.23 ± 0.12	1.22 ± 0.25	1.17 ± 0.12
Number of chews	27.62 ± 12.00	27.04 ± 11.93	30.22 ± 10.95
Consumption time per bite [s]	21.45 ± 9.19	19.25 ± 8.77	22.35 ± 8.78
Chewing cycle duration [s/chew]	0.78 ± 0.13	0.73 ± 0.15	0.75 ± 0.16
Chewing rate [chew/s]	1.31 ± 0.21^a	1.46 ± 0.48^b	1.39 ± 0.29^b
Average bite size [g]	4.05 ± 1.56	3.29 ± 1.08	3.49 ± 1.32
Eating rate [g/s]	0.21 ± 0.10	0.20 ± 0.10	0.17 ± 0.06

Legend: T_1 is the shortest grilling time; T_2 is medium grilling time; T_3 is the longest grilling time. Testing was performed in three replicates. The panel consisted of 10 panelists. Note: items denoted with different letters are significantly different at the level of 5%.

processing methods used, one 2-hour session was organized as suggested by Djekic et al. [37].

2.5. Temporal Dominance of Sensations. For performing TDS evaluation, six sensory characteristics have been predefined, as follows: firm, meat flavor, juicy, dry, fibrous, and soft, modified from References [9, 38, 39]. The meanings of each sensation were explained to the panelists [40] during the first training session for sensory evaluation. Definitions that were used were as follows: firm/soft-strong/weak force required to compress food between molars; juicy/dry-high/low quantity of juice released from food during mastication; fibrous—the presence of fibers in meat samples; meat flavor—the strength of all flavors typical for pork/poultry meat. Reference food used during the training session was pork and poultry meat prepared in three culinary methods—grilling, cooking in boiling water, and *sous-vide*. Also, panelists were instructed to select a dominant sensation only when they perceived one, and they could choose the same attribute more than once.

The grilled meat was cut into cubical samples ($20 \times 20 \times 20$ mm) and provided to panelists for TDS. This test was completed using an internally developed application and in line with the method explained in Djekic et al. [9]. When mastication started, the panelists selected "start," and dominant sensations were recorded. At the moment of swallowing, panelists were instructed to select "stop." Testing of all grilled samples (two types of meat, three grilling temperatures) was performed in three replications. Samples, coded with three-digit codes, were served to the panelists randomly, one at a time on two consecutive days—the first day for pork meat and the second day for poultry meat. To clean the palates and remove aftertastes between two mastications, panelists used white bread and tap water.

To calculate TDS curves, the following rules have been applied: for each point on the time scale, the value of the dominance rate (overall share of a specific attribute) was determined by dividing the number of mentions of a sensation divided by the overall number of sampling (from all replications and panelists) [41]. The "rule of the thumb" in interpreting the curves is that "the higher the proportion, the higher the agreement among panelists about the dominating sensation over the period." All plotted results were standardized from the first bite to swallowing [9, 42].

2.6. Oral Processing. The grilled meat was cut into cubical samples ($20 \times 20 \times 20$ mm) and presented to panelists for mastication. The mass of every sample was measured with a technical balance of 0.01 g accuracy. A digital video camera was positioned in front of the panelist, so the upper part of the person chewing was visible, as proposed by Forde et al. [35]. All members of the panel chewed all grilled samples (two types of meat, three grilling temperatures) in three replications. Upon completion, video clips have been analyzed using a stopwatch, resulting in the number of chews and total oral exposure time [43, 44].

Based on these data, the following oral processing parameters have been calculated: the number of chews, consumption time per sample, chewing cycle duration (s/chew), chewing rate (chews/s), eating rate (g/s), and average bite size (g) [4, 35].

2.7. Mechanical Properties. Mechanical properties of two types of meat samples have been determined under atmospheric temperature/pressure conditions (20°C, 1 atm) using Brookfield CT3 Texture Analyser for compression and TA.XT plus Texture Analyser, Stable Micro System for Warner–Bratzler shear tests. Compression test parameters were as follows: test type—compression, test speed—1 mm/s, trigger load—10 g, target mode—30%, load cell—10 kg, probe selection—cylindrical probe (plate of 50.8 mm

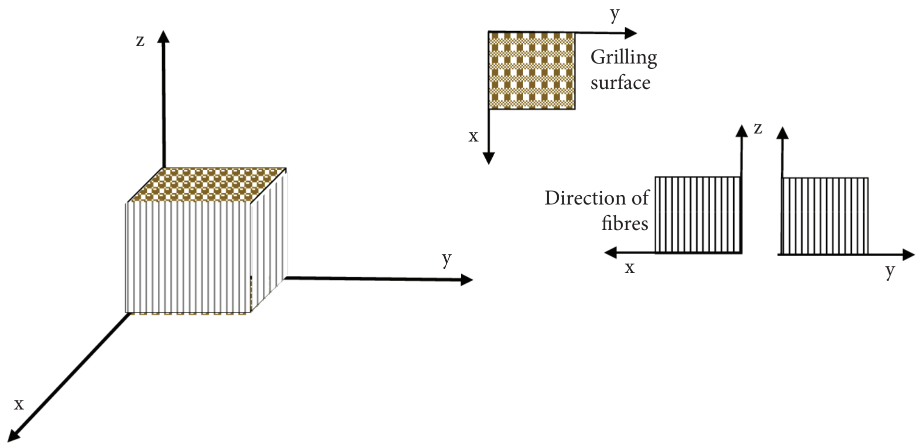


Figure 1: Orthogonal isometric view of the 3D model of cubic meat pieces with defined grilling surface.

diameter), and sample shape—rectangular. This test was performed on all three planes of the cubic sample (Figure 1).

Warner–Bratzler shear test had the following parameters: test speed—1 mm/sec, target mode—distance (21 mm), sample shape–rectangular, selected probe—HDP/WBV (Warner-Bratzler V slot blade), and load cell—50 kg. This test was performed normally on the axis of the muscle fibers [9]. In such a way, the tool cuts the samples, so the shearing is perpendicular to the longitudinal positioning of the fibers [45].

All meat samples that were cut off along the axis of the muscle fibers had cubic dimensions (20 × 20 × 20 mm), and tests were performed in 15 replicates. Dimensions of the samples were manually measured with a digital vernier caliper. Preparation of the samples was performed using thin-bladed sharp knives to minimize the damage to the fibers and take into account the direction of the fibers [46]. As an output of this test, firmness (N) was obtained.

True stress and strain calculations have been obtained according to the research of Vallespir et al. [47] and Vicente [48] (equations (1) and (2)). Rupture stress (σ_R, MPa) and strain (ε_R) have been extracted from the first peak of the stress-strain curve using TexturePro CT V1.9 Build 35 software. Young's modulus (E_d) was calculated for the common linear part of the stress-strain curve (equation (3)).

$$\sigma_R = \frac{F(t) * (H_o - H(t))}{A_o * H_o}, \quad (1)$$

$$\varepsilon_R = \ln \frac{H_o}{H_o - \Delta H}, \quad (2)$$

$$E_d = \frac{\sigma_R}{\varepsilon_R}. \quad (3)$$

Legend: $F(t)$ is the force at time t; H_o is the initial sample height; ΔH is the height difference; $H(t)$ is the height at time t; and A_o is the sample area.

From material science, it is known that depending on the mechanical properties under load, isotropic materials are the ones directionally independent as opposed to orthotropic (interchangeable across the three orthogonal axes) or anisotropic having different properties in all directions [32]. As meat is a complex material, for this study, it was considered an orthotropic material with three planes/axes of symmetry (Figure 1). Therefore, the calculation of all the abovementioned parameters has been performed for all three planes.

To calculate Poisson's ratio, it has been assumed that during compression tests, expansion of meat in the direction perpendicular to the specific loading direction is equal in the other two planes with constant volume before and after loading, equations (4) and (5):

$$V_b = V_a, \quad (4)$$

$$x \cdot y \cdot z = (x - \Delta x) \cdot (y + \Delta y) \cdot (z + \Delta z), \quad (5)$$

where V_b is the volume of the sample before compression; V_a is the volume of the sample after compression; x, y, and z are the lengths of the cube in three planes; assumed compression axial to x-axis.

Poisson's ratio as the ratio between the transversal (lateral) strain and the longitudinal strain, in a tensile or compressive test, is presented as follows:

$$\nu_{ij} = -\frac{\varepsilon_j}{\varepsilon_i}, \quad (6)$$

where ν_{ij} is corresponding to an expansion in direction when compression is applied in direction.

2.8. Simulation of the First Bite. In this study, a 3D solid model of grilled meat was created by using solid modelling software. The mesh has been developed in the SolidWorks Simulation FEM code. The tetrahedral solid element type was chosen with 34,146 elements and 40,228 nodes used for mesh construction of the 3D model. A similar mesh was used in the work of Wang and Sun [21] that modeled roasted meat with four-node tetrahedral elements.

For the purpose of performing this simulation, the following assumptions apply: (i) 3D solid meat is presented as a cube (20 × 20 × 20 mm); (ii) first bite occurs perpendicular to the longitudinal positioning of the fibers; (iii) first

Table 3: Summary of the oral processing behavior parameters for poultry meat samples prepared using three grilling working regimes.

	Poultry meat		
	T_1	T_2	T_3
Density [g/cm^3]	1.15 ± 0.12	1.11 ± 0.07	1.10 ± 0.07
Number of chews	22.16 ± 7.69	23.00 ± 8.35	23.46 ± 9.01
Consumption time per bite [s]	16.00 ± 6.01	17.17 ± 6.05	16.85 ± 5.96
Chewing cycle duration [s/chew]	0.73 ± 0.15	0.76 ± 0.15	0.74 ± 0.14
Chewing rate [chew/s]	1.42 ± 0.26	1.36 ± 0.24	1.39 ± 0.26
Average bite size [g]	2.85 ± 1.07	2.53 ± 0.92	2.63 ± 0.91
Eating rate [g/s]	0.20 ± 0.09	0.16 ± 0.06	0.17 ± 0.08

Legend: T_1 is the shortest grilling time; T_2 is medium grilling time; T_3 is the longest grilling time. Testing was performed in three replicates. The panel consisted of 10 panelists. Note: no statistically significant difference was observed at the level of 5% ($p > 0.05$).

bite occurs parallel to the x-axis; (iv) first-bite force was assumed as the value obtained from WB test for all types of grilled meat (Table 3) divided by two (upper and lower jaw); and (v) first bite was calculated as line pressure (20 mm) assuming teeth (incisors) width of 1 mm. To simulate the first bite, values for density, Young's modulus, and Poisson's ratio for the three orthogonal axes will be used.

2.9. Statistical Processing. One-way ANOVA and Tukey's HSD post hoc tests were used to distinguish statistical differences between grilling time as the heating factor, while meat type was not considered as factor for statistical analysis. The level of statistical significance was set at 0.05.

3. Results and Discussion

3.1. Oral Processing Characteristics. Tables 2 and 3 give an overview of oral processing parameters for two types of meat. For pork meat, (Table 2) the number of chews was between 27 and 30, with an average mastication time between 19 and 22 seconds. The chewing cycle was around 0.75 s/chew, with the chewing rate up to 1.46 chews/s. The lowest average bite size was for medium grilling time. Oral processing characteristics of poultry meat (Table 3) fall in a narrower range: number of chews between 22 and 24; chewing cycle between 0.73 s/chew and 0.76 s/chew, and chewing rate up to 1.42 chews/s. More pronounced differences between the number of chews were observed for pork meat (Table 2) grilled at the highest temperature compared to poultry meat (Table 3), but with no statistical difference ($p > 0.05$). This pattern is expected as higher temperatures trigger crust formation and heat-related toughening associated with harder meat [25].

The chewing rate was the only parameter with an observed statistical difference (only for pork meat) with values in the range of 1.31 chews/s-1.46 chews/s (pork meat, Table 2) and 1.36 chews/s-1.42 chews/s (poultry meat, Table 3). These values are slightly below the mean chewing rate of 1.53 chews/s outlined by Farooq and Sazonov [49]. It needs to be mentioned that meat as a very complex material influences oral processing parameters to fall out of typical, expected patterns observed in solid food such as cheese or chocolate [4]. Mastication pattern is influenced by the mechanical properties of meat, a mixture of saliva and liquid released from the meat, and culinary treatment applied to meat [9, 50, 51].

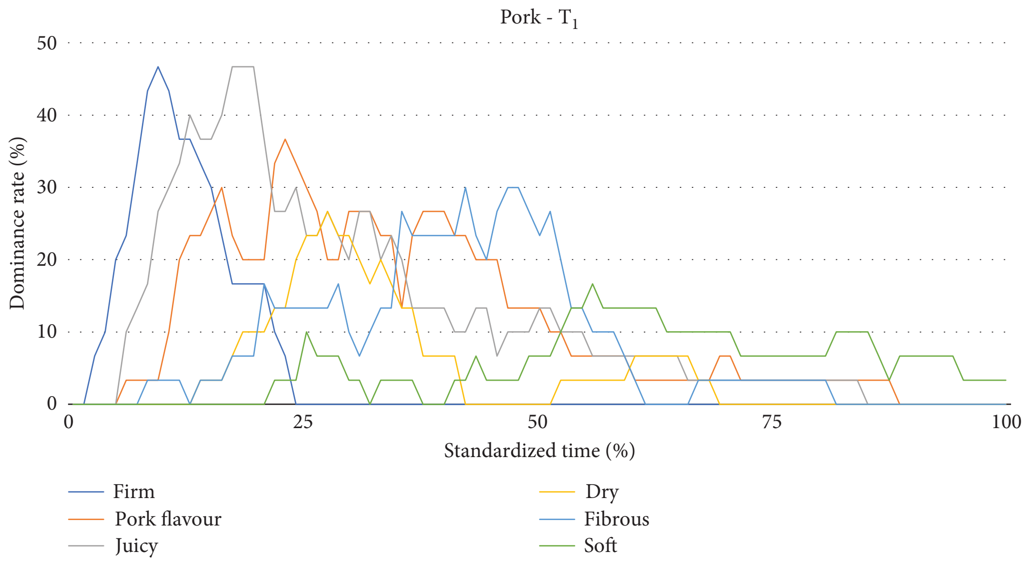
3.2. Temporal Dominance of Sensations. When the aim of performing sensory analysis is to examine textural and flavor changes during mastication, TDS is recognized as one of the most promising tools and has been used in meat science [7, 9]. It is a dynamic sensory method with the aim of capturing "dominant sensation(s)" while consuming food [52]. Grilled meat is unique in its flavor and taste, and grilling is one of the most popular culinary methods used at home and/or restaurants [53]. A similar approach in employing TDS with pork loins was performed by Watanabe et al. [54].

Figure 2 presents the results of TDS applied on evaluating pork and meat products treated under three grilling temperatures, showing the proportion of citations for each sensory attribute. The firmness of the samples dominated in pork meat products during the beginning of mastication, similar to the results of Watanabe et al. [54]. In parallel, juiciness (for T_1 and T_2) and dry attribute (for T_3) dominate until half of the consumption time. These patterns may have been expected as culinary methods using temperatures above 140°C enable the development of odor and meat flavors [55], preventing juice losses and textural damages [56]. In the second half of the mastication process, the softness of the sample (and bolus) was predominant. For all three grilling times, in the last third of the mastication period, no sensation had over 30% of dominance rate.

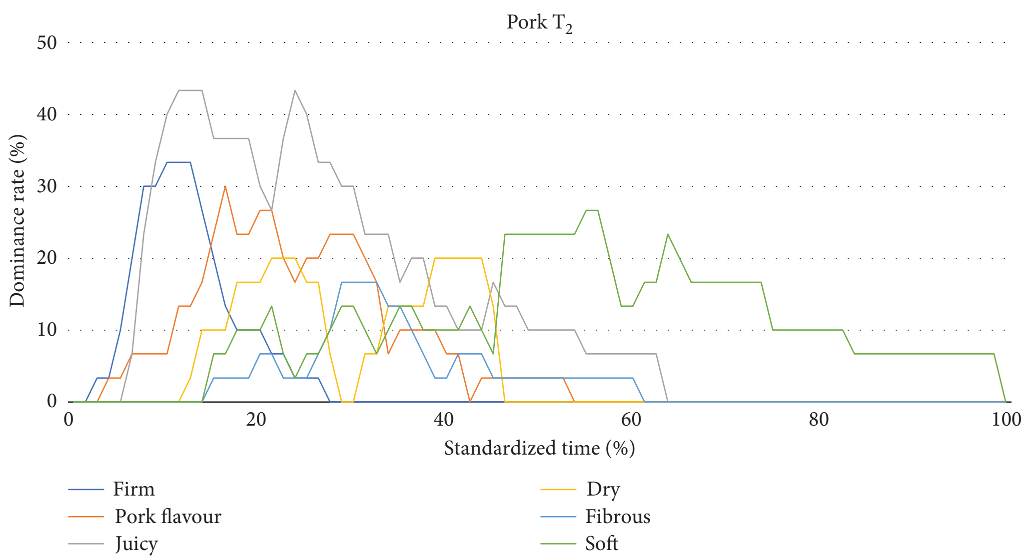
As for poultry meat, the flavor was very dominant at the beginning of the chewing process for T_1, with firmness being firstly observed by panelists for T_2 and T_3. Juiciness was recognized as the most dominant in the middle of the mastication period. During the last period of mastication, similar to pork meat, softness was prevailing. Knowing that poultry meat is slightly softer than pork meat, it is not surprising that flavor and juiciness are observed at the beginning of the consumption process, as chewing affects the perception of juiciness [57] and the release of aroma [52].

For both types of meat, at T_3, the dry sensation was also observed by panelists due to the fact that the final internal temperature of pork and poultry at the longest grilling time was the highest, corresponding to previous research that internal temperature above 80°C decreases tenderness [58, 59]. As the first dominant attribute, "firmness" is common for all samples; this finding is valuable for understanding how to simulate the first bite.

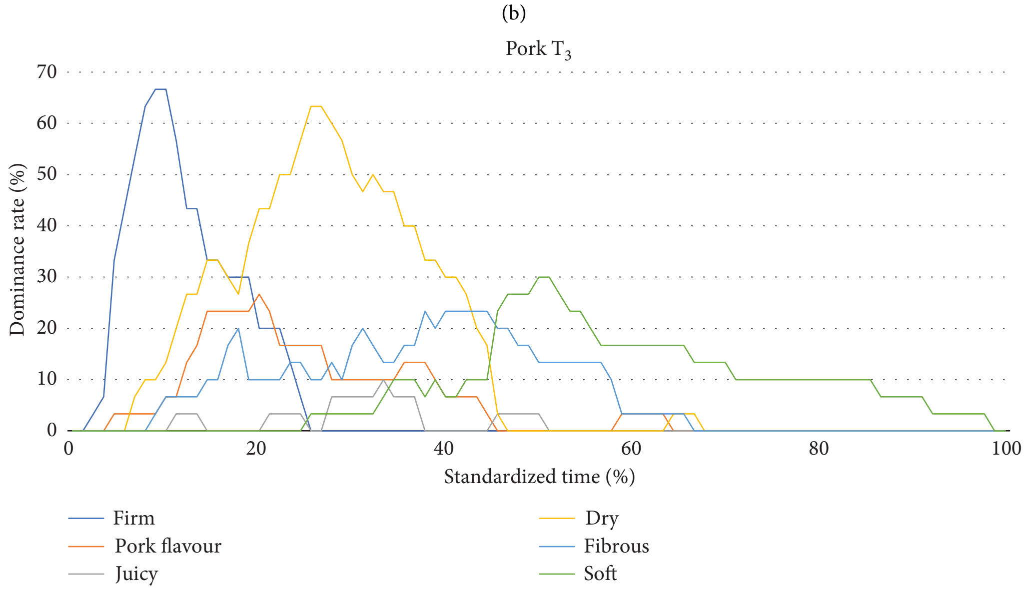
3.3. Mechanical Properties. From Figure 1, it is obvious that the grilling surface was set on the plane perpendicular to fibers (plane xOy). A higher level of cooking loss was observed for poultry meat (up to 40%) than that of pork meat (almost 30%) (Table 4). Firmness obtained by the Warner–Bratzler shear



(a)

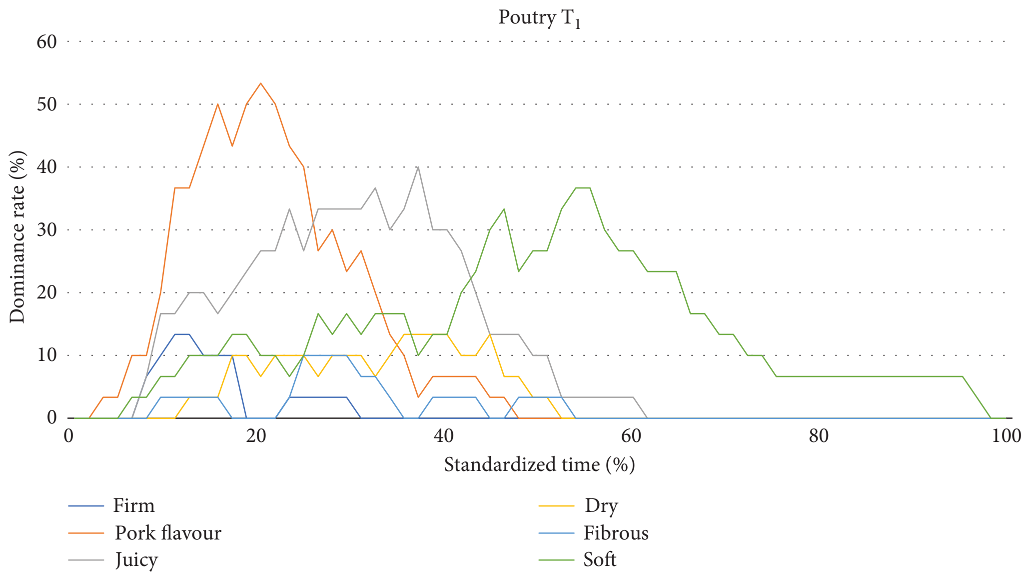


(b)

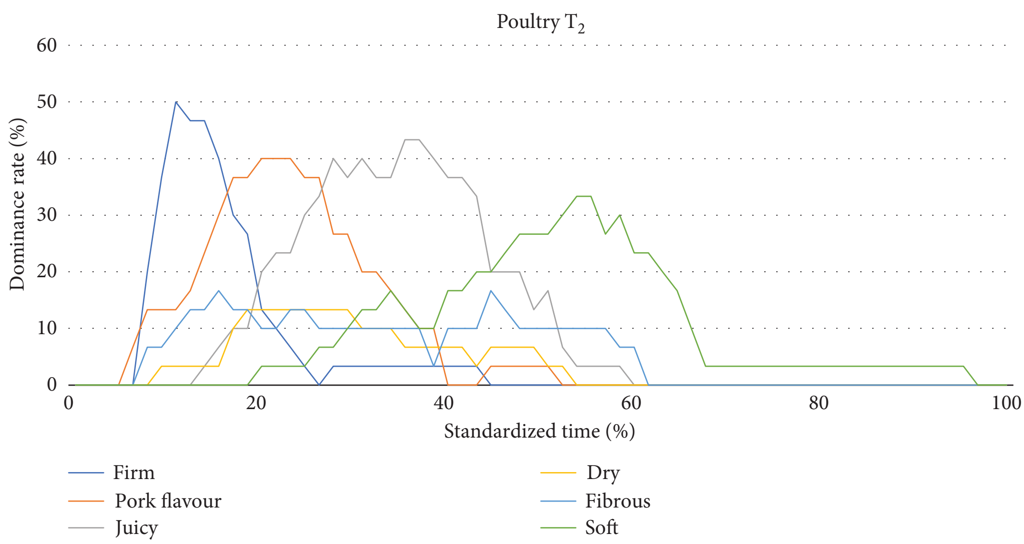


(c)

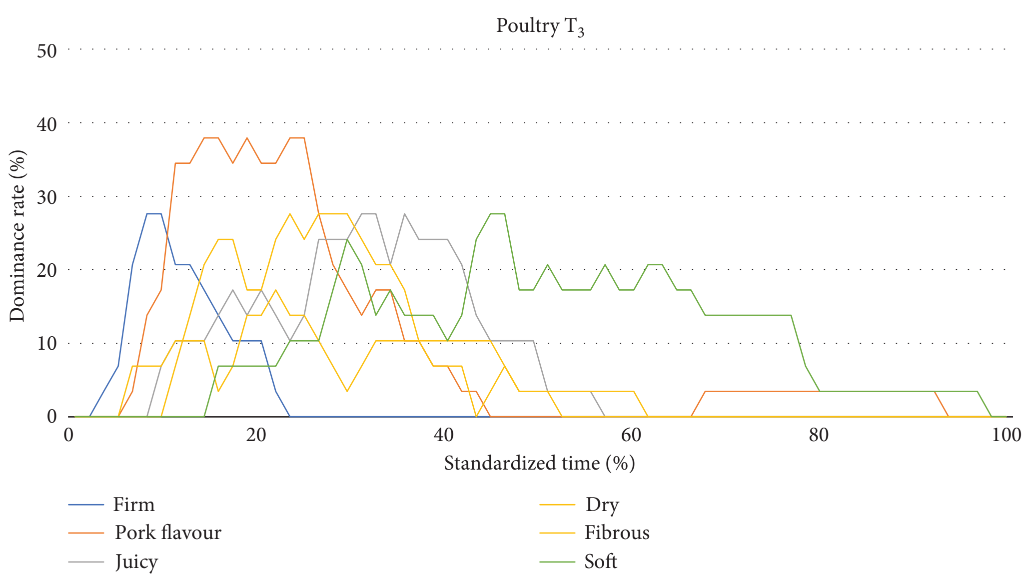
Figure 2: Continued.



(d)



(e)



(f)

FIGURE 2: Temporal dominance sensation (TDS) curves for pork meat (a-c) and poultry meat (d-f) for three grilling temperatures methods. Defined time axis from $t = 0$ (first bite—0%) to $t = 1$ (swallowing—100%). Attributes are shown in different colors.

Table 4: Summary of mechanical properties for samples prepared using three grilling temperatures.

	Pork meat			Poultry meat		
	T_1	T_2	T_3	T_1	T_2	T_3
Cooking loss [%]	6.33 ± 0.45^{a}	13.57 ± 1.44^{b}	29.76 ± 2.94^{c}	27.01 ± 1.43^{a}	29.98 ± 2.84^{a}	40.92 ± 6.74^{b}
Storage loss [%]	2.47 ± 0.68^{a}	1.41 ± 0.32^{b}	1.20 ± 0.44^{b}	1.46 ± 0.13^{a}	3.07 ± 0.54^{b}	1.04 ± 0.18^{a}
Firmness [N]—WB test	58.20 ± 10.01^{a}	$65.40 \pm 16.16^{a,b}$	79.30 ± 31.13^{b}	34.00 ± 5.30^{a}	35.80 ± 6.24^{a}	42.80 ± 11.70^{b}
Maximum shear force [N]	79.12 ± 19.86^{a}	61.37 ± 13.19^{b}	55.21 ± 11.26^{b}	31.09 ± 15.82	40.37 ± 22.28	45.77 ± 14.18
Young's modulus—E_x [Kpa]	35.05 ± 11.22^{a}	75.28 ± 35.92^{b}	111.14 ± 23.21^{c}	35.18 ± 8.48^{a}	$50.25 \pm 20.68^{a,b}$	74.36 ± 29.23^{b}
Young's modulus—E_y [Kpa]	28.49 ± 6.44^{a}	$57.03 \pm 30.38^{a,b}$	126.83 ± 68.89^{b}	30.62 ± 9.67	35.17 ± 24.39	39.21 ± 15.4
Young's modulus—E_z [Kpa]	40.83 ± 14.44^{a}	54.34 ± 49.27^{a}	146.83 ± 86.58^{b}	34.94 ± 15.45^{a}	$45.85 \pm 20.78^{a,b}$	62.82 ± 19.24^{b}
Poisson's ratio—ν_{xy}	0.3631	0.4885	0.4913	0.2296	0.3046	0.3498
Poisson's ratio—ν_{yz}	0.3641	0.3680	0.4814	0.3663	0.4861	0.4909
Poisson's ratio—ν_{zx}	0.2460	0.3192	0.3895	0.3072	0.3193	0.3239

Note: items denoted with different letters are significantly different at the level of 5%.

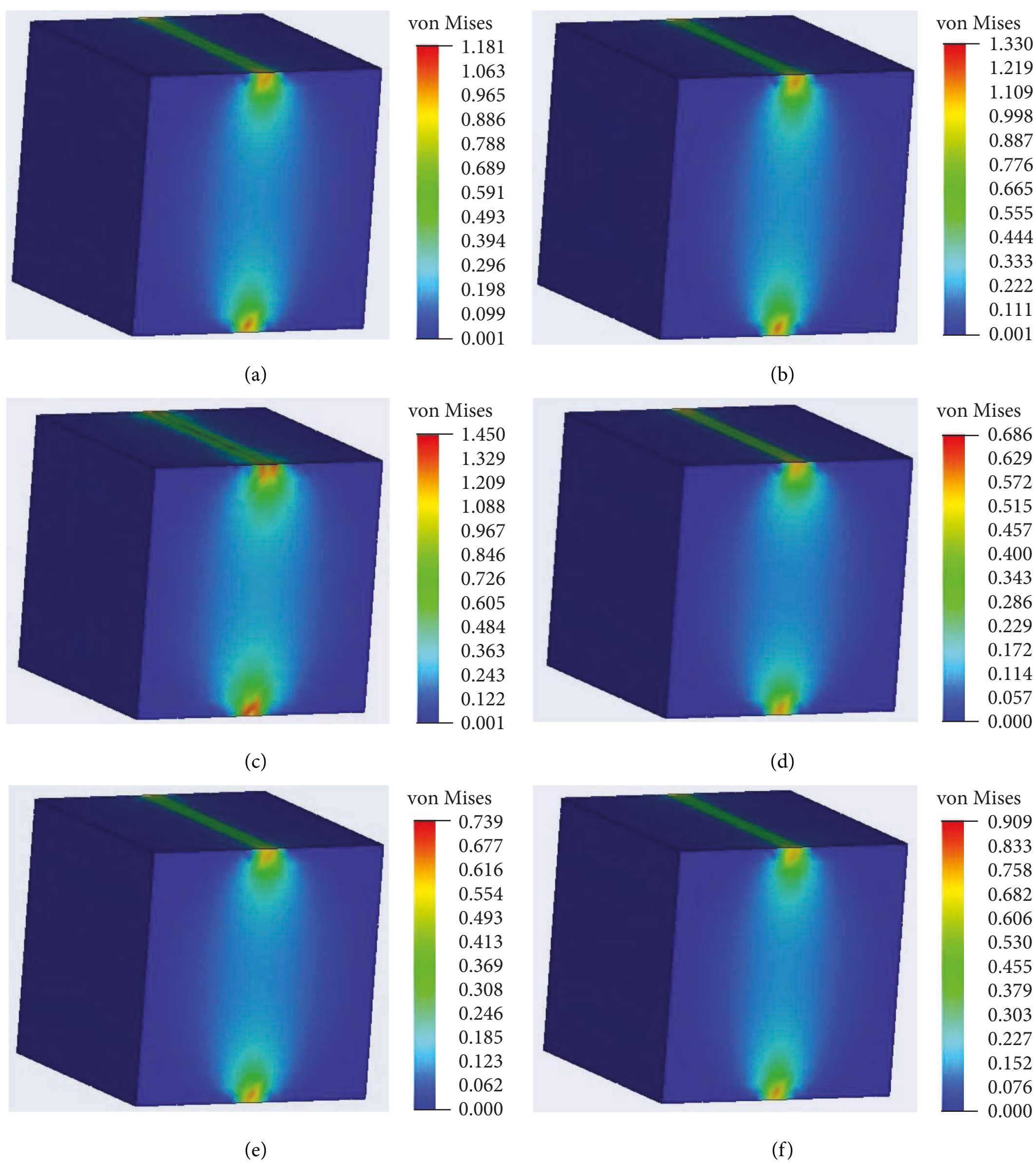


Figure 3: Stress distribution during the impact of the upper and lower jaw is shown for six samples: (a) pork meat T_1; (b) pork meat T_2; (c) pork meat T_3; (d) poultry meat T_1; (e) poultry meat T_2; and (f) poultry meat T_3. The color scale bar indicates gradient areas (from maximum to minimum) of von Mises stress (N/mm^2) in the direction of pressure.

force test shows that the values increase with the increase in grilling temperature. This test measures the maximum force needed to cut off/shear a meat sample [45], and this value was used for modelling the first bite.

Values of Young's modulus increase with the increase in grilling temperature. On the other side, due to the complexity of meat, values of this modulus differ on all three planes with no clear pattern. The Poisson's ratio was between 0.2460 and 0.4913 for pork and between 0.2296 and 0.4909 for poultry meat. Young's modulus in the study of Jahanbakhshian et al. [60] for chicken nugget crust and the crumb was 0.26 and 0.37, respectively. Kim and Hung [61] reported that Poisson's ratio of meat products was in the range of 0.2 to 0.4, while in the work of Nowak et al. [62], the average value of Poisson's ratio of various meat products was 0.49. Most soft tissues are considered roughly incompressible materials with a Poisson ratio up to 0.49 [63]. This means that if the tissue is compressed axially (in one direction), then it must expand laterally in the other two directions [64]. This assumption was used in our study to calculate Poisson's ratio values in all three directions.

3.4. First Bite Simulation. For simulating the first bite, calculated values for density, Young's modulus, and Poisson's ratio for the three orthogonal axes (Tables 2–4) have been used to set the parameters of meat as an orthotropic material. Six models have been developed (pork meat T_1, pork meat T_2, pork meat T_3, poultry meat T_1, poultry meat T_2, and poultry meat T_3). Pressures applied at the first bite were in the range of 1.46-1.98 N/mm^2 (pork) and 0.85-1.07 N/mm^2 (poultry). Values were calculated using firmness values for the Warner–Bratzler test divided by 40 (length of incisors that adhere to the surface 20 mm, incisors width 1 mm, 2 jaws—upper and lower and assuming both jaws have equal pressure, so we have pressure area of 20 mm^2 for the upper jaw and the same value for the lower jaw, in total 40 mm^2).

According to the FEM simulation results, maximum values for von Mises stress were obtained for the highest grilling temperatures (1.98 N/mm^2 for pork meat T_3 and 1.07 N/mm^2 for poultry meat T_3). The von Mises stress is often used in biomechanical calculations as the stress value enables predicting the food damage behavior [65].

A comparison of results shows that higher grilling time corresponds to higher values of van Mises stress for both types of meat. Values of maximum von Mises stress rise from 1.181 N/mm^2 to 1.450 N/mm^2 for pork and from 0.686 N/mm^2 to 0.909 N/mm^2 for poultry meat. These computed values by using FEM enable prediction of how deformation will occur during the first bite [12], knowing that the average duration of the chewing cycle (and the first bite) is between 0.73 and 0.78 s/chew for both types of meat (Tables 2 and 3). The 3D models (Figure 3) show the development of internal stress in the first-bite direction leading to crack propagation and breakage of the sample by the pressure of the upper and lower jaw as expected during the first bite. The highest values for all six samples are in the area of teeth pressure, indicating that upon impact, the structure will most probably experience irreversible damage leading to diving the sample into two pieces. These results show that the use of FEM in combination with experimental data associated with food materials may enable fair prediction of crack initiation and propagation [66]. This is the first step in modelling the food mastication cycle from first bite breakdown, the interactions between comminuted food and saliva during bolus formation, to the release and transport of taste and aromas [67]. Future challenges in modelling oral digestion should focus on (i) widening the perspective of understanding mechanic of food to how they flow/deform during mastication and (ii) understanding physicochemical reactions supported by the role of enzymes in the dissolution of taste compounds into saliva and release of aromatics in the mouth [68].

TDS curves give an overall perception of major sensory attributes of grilled pork meat during mastication. It is obvious that differences in the dynamic sensory perception of the samples exist in terms of whether textural or taste/odor attributes prevail, depending on the type of meat and grilling parameters. However, as firmness was the predominant sensory attribute recognized by a panelist at the beginning of mastication, simulation of the first bite using mechanical characteristics may pave the way for simulating the entire grilled meat mastication process. Overall, chewing cycles mainly serve for food breakdown initiating it from the first bite [52]. In parallel, when mastication starts, it triggers saliva incorporation in the mouth acting as a solvent for releasing different taste-active compounds [69]. Awareness of in-mouth changes obtained during TDS may be useful not only for interpreting TDS graphs but also for designing new types of food associated with recognized sensory profiles [70]. However, it must be mentioned that as in the case of all types of organic materials, the complexity of the material, variability of different impacts, and sample orientation influence results [12].

4. Implications for Sensory Science

This paper provides new insights into explaining changes in mechanical properties, mastication, and dynamic sensory perception of grilled meat ending with the modelling of the first bite. In addition to the increased need for understanding food oral processing and digestion [71, 72], authors believe that the application of such modelling can help in revealing not only food breakdown [73, 74] but also flavor release [1], important in gastronomy and sensory science. Our results send a message that a variety of mastication aspects should be considered for understanding different gastronomic factors associated with grilled meat. By considering the information provided in this paper, chefs may find ideas for adapting grilling methods for target groups of meat consumers. Finally, results may be also of interest to various gastronomy stakeholders in the future development of tailor-made food for different groups of consumers such as the elderly, dental wearers, or children.

5. Conclusions

This study highlights the potential of using finite element modelling in oral processing studies and is one of the first of its kind that tried to connect mechanical properties in modelling the first bite. This approach has been used as a first step in simulating meat behavior during mastication, as TDS confirmed that the firmness of grilled meat is a sensation attributed to the first bite while oral processing showed that regardless of the type of grilled meat and grilling temperature used, duration of the first bite is between 0.73 s and 0.78 s. This model may be a starting point in defining more accurate methods for simulating the mastication of complex solid materials such as meat.

The limitation of the study may be the fact that the simulation of the first bite was based only perpendicular to the fibers considering that the direction of fibers during the first bite may not be relevant to average consumers. Also, realistic jaw motions as well as the geometry and rigidity of the teeth have been simplified.

Future research on 3D modelling of the mastication process of pork meat could include mechanical properties of meat bolus at different stages of mastication, including saliva incorporation that affects changes observed during TDS.

Data Availability

Data are available upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

The results within this research originated from a Proof of Concept project #5229 "Design of artificial masticator for modelling food oral processing" financed by the Innovation Fund from the budget of the Government of the Republic of Serbia, the Ministry of Education, Science and Technical Development through the "Competitiveness and Jobs Project."

References

[1] J. Chen, "Food oral processing: some important underpinning principles of eating and sensory perception," *Food Structure*, vol. 1, no. 2, pp. 91–105, 2014.

[2] P. J. Lillford, "The importance of food microstructure in fracture physics and texture perception," *Journal of Texture Studies*, vol. 42, no. 2, pp. 130–136, 2011.

[3] K. Hiiemae, M. Heath, G. Heath et al., "Natural bites, food consistency and feeding behaviour in man," *Archives of Oral Biology*, vol. 41, no. 2, pp. 175–189, 1996.

[4] M. G. Aguayo-Mendoza, E. C. Ketel, E. van der Linden, C. G. Forde, B. Piqueras-Fiszman, and M. Stieger, "Oral processing behavior of drinkable, spoonable and chewable foods is primarily determined by rheological and mechanical food properties," *Food Quality and Preference*, vol. 71, pp. 87–95, 2019.

[5] I. Djekic, J. Ilic, R. P. F. Guine, and I. Tomasevic, "Can we understand food oral processing using kano model? case study with confectionery products," *Journal of Texture Studies*, vol. 51, no. 6, pp. 861–869, 2020.

[6] A. K. Young, J. N. Cheong, D. I. Hedderley, M. P. Morgenstern, and B. J. James, "Understanding the link between bolus properties and perceived texture," *Journal of Texture Studies*, vol. 44, no. 5, pp. 376–386, 2013.

[7] A. Rizo, E. Pena, A. Alarcon-Rojo, S. Fiszman, and A. Tarrega, "Relating texture perception of cooked ham to the bolus evolution in the mouth," *Food Research International*, vol. 118, pp. 4–12, 2019.

[8] N. Pematilleke, M. Kaur, B. Adhikari, and P. Torley, "Influence of meat texture on oral processing and bolus formation," *Journal of Food Engineering*, vol. 283, 2020.

[9] I. Djekic, J. Ilic, J. M. Lorenzo, and I. Tomasevic, "How do culinary methods affect quality and oral processing characteristics of pork ham?" *Journal of Texture Studies*, vol. 52, no. 1, pp. 36–44, 2021.

[10] J. Chen, "Food oral processing—a review," *Food Hydrocolloids*, vol. 23, no. 1, pp. 1–25, 2009.

[11] X. Wang and J. Chen, "Food oral processing: recent developments and challenges," *Current Opinion in Colloid & Interface Science*, vol. 28, pp. 22–30, 2017.

[12] H. K. Celik, A. E. Rennie, and I. Akinci, "Deformation behaviour simulation of an apple under drop case by finite element method," *Journal of Food Engineering*, vol. 104, no. 2, pp. 293–298, 2011.

[13] S. Yousefi, H. Farsi, and K. Kheiralipour, "Drop test of pear fruit: experimental measurement and finite element modelling," *Biosystems Engineering*, vol. 147, pp. 17–25, 2016.

[14] S. Haiyan, W. Fang, Z. Jianguo, Z. Yinong, and Y. Shugang, "Finite element analysis of mechanical characteristics of dropped eggs based on fluid-solid coupling theory," *Shock and Vibration*, vol. 2017, Article ID 4512497, 7 pages, 2017.

[15] S. Guessasma, L. Chaunier, and D. Lourdin, "Finite element modelling of the mechanical behaviour of vitreous starch/protein composite," *Journal of Food Engineering*, vol. 98, no. 2, pp. 150–158, 2010.

[16] S. Ishigaki, T. Nakano, S. Yamada, T. Nakamura, and F. Takashima, "Biomechanical stress in bone surrounding an implant under simulated chewing," *Clinical Oral Implants Research*, vol. 14, no. 1, pp. 97–102, 2003.

[17] H. Saini, D. C. Ackland, L. Gong, Cheng, and O. Rohrle, "Occlusal load modelling significantly impacts the predicted tooth stress response during biting: a simulation study," *Computer Methods in Biomechanics and Biomedical Engineering*, vol. 23, no. 7, pp. 261–270, 2020.

[18] B. Dejak and A. Młotkowski, "A comparison of mvM stress of inlays, onlays and endocrowns made from various materials and their bonding with molars in a computer simulation of mastication—FEA," *Dental Materials*, vol. 36, no. 7, pp. 854–864, 2020.

[19] A. Kuitche, J.-D. Daudin, and G. Létang, "Modelling of temperature and weight loss kinetics during meat chilling for time-variable conditions using an analytical-based method—I. The model and its sensitivity to certain parameters," *Journal of Food Engineering*, vol. 28, no. 1, pp. 55–84, 1996.

[20] A. Amezquita, C. Weller, L. Wang, H. Thippareddi, and D. Burson, "Development of an integrated model for heat transfer and dynamic growth of *Clostridium perfringens* during the cooling of cooked boneless ham," *International Journal of Food Microbiology*, vol. 101, no. 2, pp. 123–144, 2005.

[21] L. Wang and D.-W. Sun, "Modelling three-dimensional transient heat transfer of roasted meat during air blast cooling by the finite element method," *Journal of Food Engineering*, vol. 51, no. 4, pp. 319–328, 2002.

[22] A. Amézquita, L. Wang, and C. L. Weller, "Finite element modeling and experimental validation of cooling rates of large ready-to-eat meat products in small meat-processing facilities," *Transactions of the ASAE*, vol. 48, no. 1, pp. 287–303, 2005.
[23] M. Santos, N. Zaritzky, and A. Califano, "Modeling heat transfer and inactivation of *Escherichia coli* O157: H7 in precooked meat products in Argentina using the finite element method," *Meat Science*, vol. 79, no. 3, pp. 595–602, 2008.
[24] J. Cepeda, C. Weller, H. Thippareddi, M. Negahban, and J. Subbiah, "Modeling cooling of ready-to-eat meats by 3D finite element analysis: validation in meat processing facilities," *Journal of Food Engineering*, vol. 116, no. 2, pp. 450–461, 2013.
[25] K. Jeong, H. O, S. Y. Shin, and Y. S. Kim, "Effects of sous-vide method at different temperatures, times and vacuum degrees on the quality, structural, and microbiological properties of pork ham," *Meat Science*, vol. 143, pp. 1–7, 2018.
[26] S. V. Ángel-Rendón, A. Filomena-Ambrosio, S. Cordon-Diaz, E. R. Benitez-Sastoque, and L. I. Sotelo-Diaz, "Ohmic cooking: application of a novel technology in pork and influences on water holding capacity, cooking loss and colour," *International Journal of Gastronomy and Food Science*, vol. 17, Article ID 100164, 2019.
[27] S. K. Matarneh, E. M. England, T. L. Scheffler, and D. E. S. Gerrard, "The conversion of muscle to meat," in *Lawrie´ s Meat Science*, pp. 159–185, Elsevier, Amsterdam, Netherlands, 2017.
[28] A. E.-D. A. Bekhit, A. Carne, M. Ha, and P. Franks, "Physical interventions to manipulate texture and tenderness of fresh meat: a review," *International Journal of Food Properties*, vol. 17, no. 2, pp. 433–453, 2014.
[29] P. P. Purslow, "Intramuscular connective tissue and its role in meat quality," *Meat Science*, vol. 70, no. 3, pp. 435–447, 2005.
[30] L. A. Spyrou, "A computational multiscale modeling framework for investigating the mechanical properties of meat," *Food Structure*, vol. 26, Article ID 100161, 2020.
[31] M. Grotte, F. Duprat, E. Pietri, and D. Loonis, "Young's modulus, poisson's ratio, and lame's coefficients of golden delicious apple," *International Journal of Food Properties*, vol. 5, no. 2, pp. 333–349, 2002.
[32] M. A. Berthaume, "Food mechanical properties and dietary ecology," *American Journal of Physical Anthropology*, vol. 159, pp. 79–104, 2016.
[33] I. Tomasevic, V. Tomovic, B. Milovanovic et al., "Comparison of a computer vision system vs. traditional colorimeter for color evaluation of meat products with various physical properties," *Meat Science*, vol. 148, pp. 5–12, 2019.
[34] Q. Saleem, R. Wildman, J. Huntley, and M. Whitworth, "Material properties of semi-sweet biscuits for finite element modelling of biscuit cracking," *Journal of Food Engineering*, vol. 68, no. 1, pp. 19–32, 2005.
[35] C. Forde, N. van Kuijk, T. Thaler, C. de Graaf, and N. Martin, "Oral processing characteristics of solid savoury meal components, and relationship with food composition, sensory attributes and expected satiation," *Appetite*, vol. 60, pp. 208–219, 2013.
[36] ISO, *Sensory Analysis—General Guidelines for the Selection, Training and Monitoring of Selected Assessors and Expert Sensory Assessors*, International Organization for Standardization, Geneva, Switzerland, 2012.
[37] I. Djekic, J. M. Lorenzo, P. E. S. Munekata, M. Gagaoua, and I. Tomasevic, "Review on characteristics of trained sensory panels in food science," *Journal of Texture Studies*, vol. 52, no. 4, pp. 501–509, 2021.
[38] L. Lorido, M. Estévez, and S. Ventanas, "Fast and dynamic descriptive techniques (flash profile, time-intensity and temporal dominance of sensations) for sensory characterization of dry-cured loins," *Meat Science*, vol. 145, pp. 154–162, 2018.
[39] L. Lorido, J. Hort, M. Estevez, and S. Ventanas, "Reporting the sensory properties of dry-cured ham using a new language: time intensity (TI) and temporal dominance of sensations (TDS)," *Meat Science*, vol. 121, pp. 166–174, 2016.
[40] ISO, *Sensory Analysis—Vocabulary. 2008*, International Organization for Standardization, Geneva, Switzerland, 2008.
[41] N. Pineau, P. Schlich, S. Cordelle et al., "Temporal dominance of sensations: construction of the TDS curves and comparison with time–intensity," *Food Quality and Preference*, vol. 20, no. 6, pp. 450–455, 2009.
[42] J. N. Cheong, K. D. Foster, M. P. Morgenstern et al., "The application of temporal dominance of sensations (TDS) for oral processing studies: an initial investigation," *Journal of Texture Studies*, vol. 45, no. 6, pp. 409–419, 2014.
[43] M. Hennequin, P. Allison, J. Veyrune, M. Faye, and M. Peyron, "Clinical evaluation of mastication: validation of video versus electromyography," *Clinical Nutrition*, vol. 24, no. 2, pp. 314–320, 2005.
[44] E. Nicolas, J. L. Veyrune, C. Lassauzay, M. A. Peyron, and M. Hennequin, "Validation of video versus electromyography for chewing evaluation of the elderly wearing a complete denture," *Journal of Oral Rehabilitation*, vol. 34, no. 8, pp. 566–571, 2007.
[45] S. Novaković and I. Tomašević, "A comparison between Warner-Bratzler shear force measurement and texture profile analysis of meat and meat products: a review," in *IOP Conference Series: Earth and Environmental Science*IOP Publishing, Bristol, UK, 2017.
[46] K. O. Honikel, "Reference methods for the assessment of physical characteristics of meat," *Meat Science*, vol. 49, no. 4, pp. 447–457, 1998.
[47] F. Vallespir, O. Rodriguez, V. S. Eim, C. Rossello, and S. Simal, "Effects of freezing treatments before convective drying on quality parameters: vegetables with different microstructures," *Journal of Food Engineering*, vol. 249, pp. 15–24, 2019.
[48] A. B. Nieto, S. Vicente, K. Hodara, M. A. Castro, and S. M. Alzamora, "Osmotic dehydration of apple: influence of sugar and water activity on tissue structure, rheological properties and water mobility," *Journal of Food Engineering*, vol. 119, no. 1, pp. 104–114, 2013.
[49] M. Farooq and E. Sazonov, "Automatic measurement of chew count and chewing rate during food intake," *Electronics*, vol. 5, no. 4, p. 62, 2016.
[50] C. Yven, J. Culioli, and L. Mioche, "Meat bolus properties in relation with meat texture and chewing context," *Meat Science*, vol. 70, no. 2, pp. 365–371, 2005.
[51] L. Mioche, P. Bourdiol, and S. Monier, "Chewing behaviour and bolus formation during mastication of meat with different textures," *Archives of Oral Biology*, vol. 48, no. 3, pp. 193–200, 2003.
[52] G. Watanabe, M. Motoyama, K. Orita et al., "Assessment of the dynamics of sensory perception of wagyu beef strip loin prepared with different cooking methods and fattening periods using the temporal dominance of sensations," *Food Sciences and Nutrition*, vol. 7, no. 11, pp. 3538–3548, 2019.
[53] T. Cordeiro, O. Viegas, M. Silva et al., "Inhibitory effect of vinegars on the formation of polycyclic aromatic

hydrocarbons in charcoal-grilled pork," *Meat Science*, vol. 167, Article ID 108083, 2020.

[54] G. Watanabe, H. Ohmori, K. Tajima et al., "Relative contribution of sensory characteristics for different types of pork loin, assessed by temporal dominance of sensations," *Journal of the Science of Food and Agriculture*, vol. 99, no. 12, pp. 5516–5525, 2019.

[55] J. Ortuño, L. Mateo, M. Rodriguez-Estrada, and S. Banon, "Effects of sous vide vs grilling methods on lamb meat colour and lipid stability during cooking and heated display," *Meat Science*, vol. 171, Article ID 108287, 2021.

[56] C. Bejerholm and M. D. Aaslyng, "The influence of cooking technique and core temperature on results of a sensory analysis of pork—depending on the raw meat quality," *Food Quality and Preference*, vol. 15, no. 1, pp. 19–30, 2004.

[57] M. D. Aaslyng, C. Bejerholm, P. Ertbjerg, H. C. Bertram, and H. J. Andersen, "Cooking loss and juiciness of pork in relation to raw meat quality and cooking procedure," *Food Quality and Preference*, vol. 14, no. 4, pp. 277–288, 2003.

[58] J. Wood, G. Nute, G. Fursey, and A. Cuthbertson, "The effect of cooking conditions on the eating quality of pork," *Meat Science*, vol. 40, no. 2, pp. 127–135, 1995.

[59] S. L. Simmons, T. R. Carr, and F. K. McKElTH, "Effects of internal temperature and thickness on palatability of pork loin chops," *Journal of Food Science*, vol. 50, no. 2, pp. 313–315, 2006.

[60] N. Jahanbakhshian, N. Hamdami, and M. Shahedi, "Measurement and prediction of the mechanical properties of a two-component food during freezing," *International Journal of Food Properties*, vol. 20, no. sup3, pp. S3088–S3095, 2017.

[61] N. K. Kim and Y. C. Hung, "Freeze-cracking in foods as affected by physical properties," *Journal of Food Science*, vol. 59, no. 3, pp. 669–674, 1994.

[62] K. W. Nowak, M. Markowski, and T. Daszkiewicz, "Ultrasonic determination of mechanical properties of meat products," *Journal of Food Engineering*, vol. 147, pp. 49–55, 2015.

[63] Y.-c. Fung, *Biomechanics: Mechanical Properties of Living Tissues*, Springer Science & Business Media, Berlin, Germany, 2013.

[64] R. G. M. van der Sman, "Modeling cooking of chicken meat in industrial tunnel ovens with the flory–rehner theory," *Meat Science*, vol. 95, no. 4, pp. 940–957, 2013.

[65] X. Han, Y. Liu, F. Tchuenbou-Magaia, Z. Li, M. Khojastehpour, and B. Li, "Analysis of the collision-damage susceptibility of sweet cherry related to environment temperature: a numerical simulating method," *Journal of Food Engineering*, vol. 333, Article ID 111140, 2022.

[66] S. Le Feunteun, A. R. Mackie, and D. Dupont, "In Silico trials of food digestion and absorption: how far are we?" *Current Opinion in Food Science*, vol. 31, pp. 121–125, 2020.

[67] S. M. Harrison, P. W. Cleary, G. Eyres, M. D. Sinnott, and L. Lundin, "Challenges in computational modelling of food breakdown and flavour release," *Food & Function*, vol. 5, no. 11, pp. 2792–2805, 2014.

[68] P. W. Cleary and S. Harrison, "Modeling food digestion in the oral cavity," in *Reference Module in Food Science*Elsevier, Amsterdam, Netherlands, 2016.

[69] R. Matsuo, "Role of saliva in the maintenance of taste sensitivity," *Critical Reviews in Oral Biology & Medicine*, vol. 11, no. 2, pp. 216–229, 2000.

[70] J. R. Stokes, M. W. Boehm, and S. K. Baier, "Oral processing, texture and mouthfeel: from rheology to tribology and beyond," *Current Opinion in Colloid & Interface Science*, vol. 18, no. 4, pp. 349–359, 2013.

[71] A.-I. Mulet-Cabero, L. Egger, R. Portmann et al., "A standardised semi-dynamic in vitro digestion method suitable for food—an international consensus," *Food & Function*, vol. 11, no. 2, pp. 1702–1720, 2020.

[72] A. Brodkorb, L. Egger, M. Alminger et al., "INFOGEST static in vitro simulation of gastrointestinal food digestion," *Nature Protocols*, vol. 14, no. 4, pp. 991–1014, 2019.

[73] Y. Pascua, H. Koç, and E. A. Foegeding, "Food structure: roles of mechanical properties and oral processing in determining sensory texture of soft materials," *Current Opinion in Colloid & Interface Science*, vol. 18, no. 4, pp. 324–333, 2013.

[74] J. Chen, "Food oral processing: mechanisms and implications of food oral destruction," *Trends in Food Science & Technology*, vol. 45, no. 2, pp. 222–228, 2015.