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Effect of foodstuff on muscle forces during biting off

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Purpose: The subject of this research is the human stomatognathic system and the process of biting off various foodstuffs. *Methods*: The research was divided into two stages – an experimental stage and a computational stage. In the first stage, tests were carried out to determine the force-displacement characteristics for the biting off food. For this purpose five different foodstuffs were tested in a testing machine and their strength characteristics were determined. The aim of the second stage was to build a computational model of the human cranium-mandible system and to run simulations of the process of biting off food in order to determine the muscular forces as a function of the food. A kinematic scheme was developed on the basis of a survey of the literature on the subject and used to create a computational model of the human stomatognathic system by means of dynamic analysis software (LMS DADS). Only the masseter muscle, the temporal muscle and the medial pterygoid muscle were taken into account – the lateral pterygoid muscle was left out. *Results*: The simulations yielded the basic kinematic and dynamic parameters characterizing the muscles. *Conclusions*: Summing up, weaker occlusion forces are needed to bite off today's foodstuffs than the forces which the mastication muscles are capable of generating. Determined in the article the general equations will enable identification of the muscular forces acting on the mandible during biting off, performing basic strength calculations, and will also give an answer to which of the products the patient after a surgical procedure will be able to consume.

Key words: *tests, numerical simulation, kinematic model of mandible-muscles system*

1. Introduction

Mandible loading is determined by the mechanics of temporomandibular joint (TMJ) in which two basic movements: the hinge movement (the lifting and lowering of the mandible) and the sliding movement (the forward and backward movement of the mandible) are executed. Also the masticatory movement, which is a combination of the above two movements, occurs in TMJ [1], [16], [18]. The mandible muscles are responsible for the execution of the movements. Two groups of the muscles are distinguished: the muscles lifting the mandible (the mastication muscles) and the muscles lowering the mandible [1], [4]. Since the mandible is either lifted or lowered it can be assumed that there exist at least two universal loading schemes (based on the same components: the support – TMJ, the active external forces – the muscular forces, the passive external forces – the support reactions, and the occlusion force) identical for all people [11], [13]. During the lifting of the mandible in the course of eating two more loading schemes, corresponding to the biting off and crushing of the bite of food, occur. However, in the literature on the subject, in both experimental studies [19] and numerical computations [26], one can find various loading schemes, depending on the research aim.

Food, as all materials, has its mechanical properties (e.g., Young's modulus, Poisson's ratio, yield point, ultimate strength and elongation) which stimulate the muscles to generate an occlusion force equal to the force which can break the particular foodstuff. In strength calculations of mechanical systems it is essential to know, besides the properties and fixing of the analyzed element, its position (here the position of the mandible relative to the jaw) corresponding to the heaviest loading. This position is

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determined mostly as part of kinematic and static calculations, but one can try to use the food's characteristic $F_s - \Delta h_s$ and the initial h_s of the bite of food to precisely determine the position of the mandible relative to the jaw, corresponding to the maximum occlusion force.

The most important stage is the determination of either the forces generated by the particular muscles, or the occlusion force, depending on the adopted loading scheme. Without knowing the loads one cannot carry out any computations concerning the deformability and strength of, e.g., a healthy jaw, the jaw after osteotomy and the jaw after resection. In the available literature it is assumed that the muscular forces are proportional to the active physiological cross section (PCS) of the muscle [25] and its bioelectric activity (Electromyography – EMG) [24] and they are determined as a function of PCS and EMG, from empirical equations [7], [24]. The occlusion forces are measured on either healthy persons [3] or on patients before and after an operation [22].

Under physiological conditions, the biggest occlusion forces occur (omitting single cases associated with, e.g., a fight, a fall, a transport accident, etc.) during meals. The foodstuff is a factor having significant influence on the loads acting on the mandible, since on the basis of the mechanical properties of the food products (mainly the value of breaking force) the brain (central and vegetative nervous system) coordinates and regulates the activity (tension) of muscles to generate an occlusion force commensurate with the food being eaten.

In the literature, there are numerous papers concerning, inter alia, changes of the texture (internal structure) of food, chewing effort, muscle activity, the number of cycles needed to prepare the bolus and food chewing [9], [10], [17], [23]. The authors of this study do not know publications which would have given the dependences (mathematical equations) enabling determination of the muscular forces depending on the consumed foodstuff. Margielewicz et al. [17] states that muscles' activity (muscular force) is connected primarily with the mechanical properties of foodstuff, the location of the bite of food on the dental arch (point of occlusion force application), which decides on the spatial position of the mandible. On this basis, it can be assumed that these dependences will be complex functions, due to the large number of variables affecting the value of muscular force (texture of food, stiffness, maximum force that can be carried by food ($F_{s\max}$), degree of moistening the food with saliva, the age, pathogenic changes).

Mastication is a highly complex activity, consisting of as many as 5 stages: (1) biting off a piece of food, (2) crushing the food, (3) moistening the food with saliva, (4) grinding and (5) pulping. Only stage 1 was analyzed as part of this study.

Based on the analysis of the chewing process a general thesis can be stated that during the preparation of a bolus, there are two extreme cases in which the greatest loads of the mandible should be expected. These are biting off and unilateral chewing (first cycle) of the same foodstuff – in each case muscles must generate an occlusion force equivalent to $F_{s\max}$. The analysis based on classical methods of analytical statics demonstrated that during biting off and chewing of the same product the muscular forces are greater at biting off than at chewing.

The act of mastication is a complex process, therefore, the authors attempted to determine the muscular forces, while biting off selected food products, based on data from experimental studies and numerical simulation. In addition, the authors want to demonstrate that the muscular forces in chewing muscles during biting off are functions of the mechanical properties of the foodstuff consumed.

The subject of research in this paper was the human cranium-mandible system. The main objectives of the research were: to determine the equations on the basis of which the muscular forces occurring during biting off food as a function of the food product could be identified; to determine the characteristics of force (F_s)–displacement (Δh_s) of food in conditions close to the natural ones; to build a computational model of the human cranium-mandible system in a computer system for dynamic analysis of multibody systems; and to perform simulations for the process of biting off food.

Calculations were made in the realm of rigid-body mechanics, i.e., limited to solving the task in the range of kinetostatics taking into account the mass forces.

2. Material and methods

In order to determine the values of muscular forces F_{ij} the computations were divided into two stages (Fig. 1). First experiments aimed at determining the force-displacement characteristics ($F_s - \Delta h_s$) and the value of maximum mean force $F_{s\max}$ needed to break food were carried out. In the second stage, numerical simulations were run to determine the values of the resultant forces (substituting for the muscular forces of three muscles) on the left (F_{wl}) and right (F_{wr})

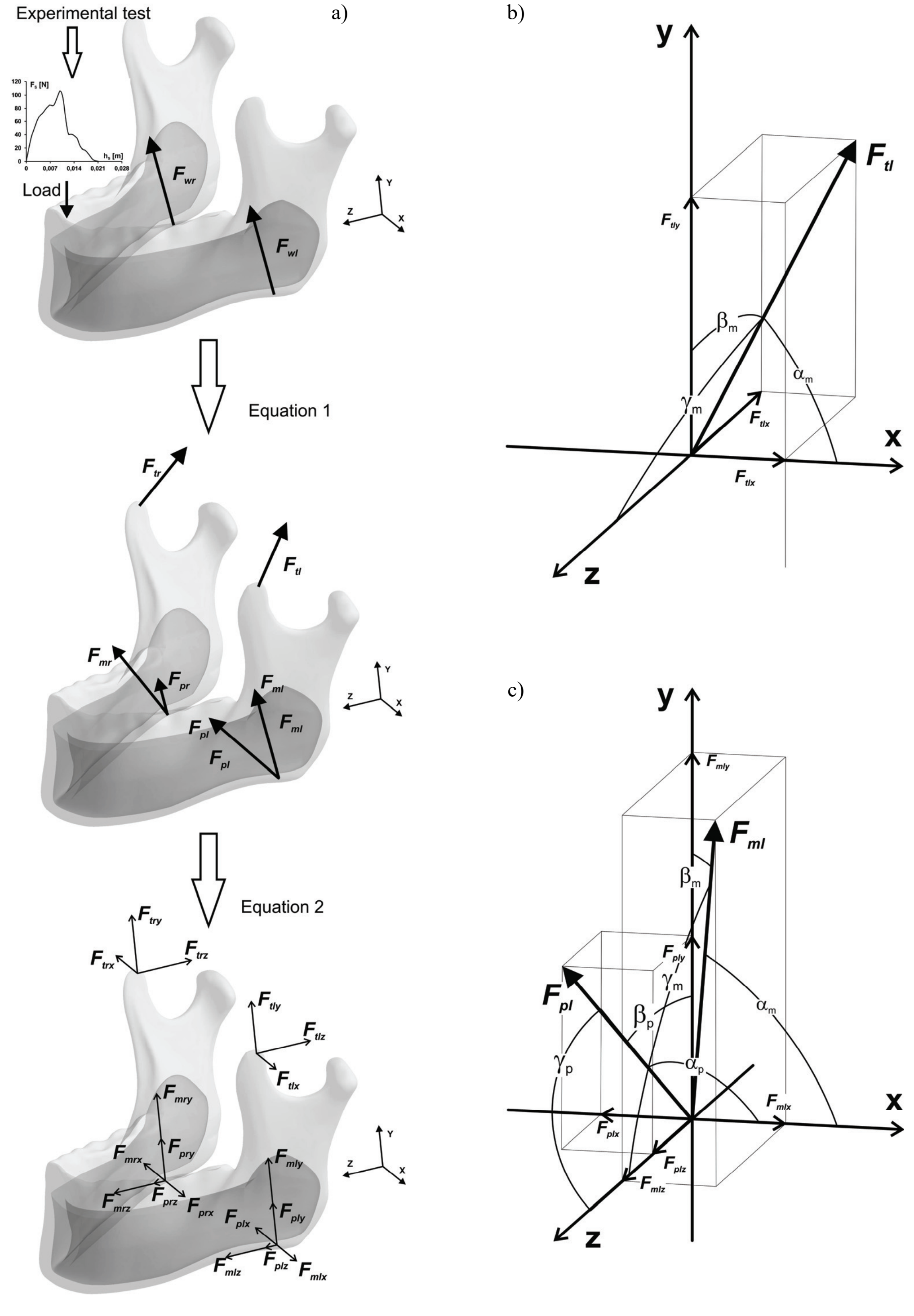


Fig. 1. Diagram showing how resultant forces F_{wl} and F_{wr} and resultant muscular forces F_{ij} (a) and their components F_{ijk} (b) and (c) are determined as a function of foodstuff

of the mandible. Then, using equations (1) and (2), the values of muscular forces (F_{ij}) of the particular muscles, and their components (F_{ijk}) were calculated. Relation coefficients $C_{m(ij)}$ and $C_{m(ijk)}$ were calculated on the basis of the data given in [27] – Table 1.

$$F_{ij} = C_{m(ij)} F_{wj} , \tag{1}$$

$$F_{ijk} = C_{m(ijk)} F_{wj} , \tag{2}$$

where

i = m (masseter), p (medial pterogoid), t (temporal),

j = l (left side), r (right side),

k = x, y, z.

Table 1. Relation coefficient values for F_{ij}^1 and F_{ijk}^1 for selected muscles

Name of Muscles	Side	Forces[1] N	Relation coefficient C_{mij}
Masseter	Left	F_{ml}	0.690
		F_{mlx}	–0.104
		F_{mly}	0.633
		F_{mlz}	0.249
	Right	F_{mr}	0.668
		F_{mrx}	0.095
		F_{mry}	0.612
		F_{mrz}	0.250
Medial pterygoid	Left	F_{pl}	0.273
		F_{plx}	0.106
		F_{ply}	0.250
		F_{plz}	0.010
	Right	F_{pr}	0.306
		F_{prx}	–0.118
		F_{pry}	0.284
		F_{prz}	0.014
Temporal	Left	F_{tl}	0.167
		F_{tlx}	–0.051
		F_{tly}	0.106
		F_{tlz}	–0.117
	Right	F_{tr}	0.138
		F_{trx}	0.035
		F_{try}	0.088
		F_{trz}	0.100

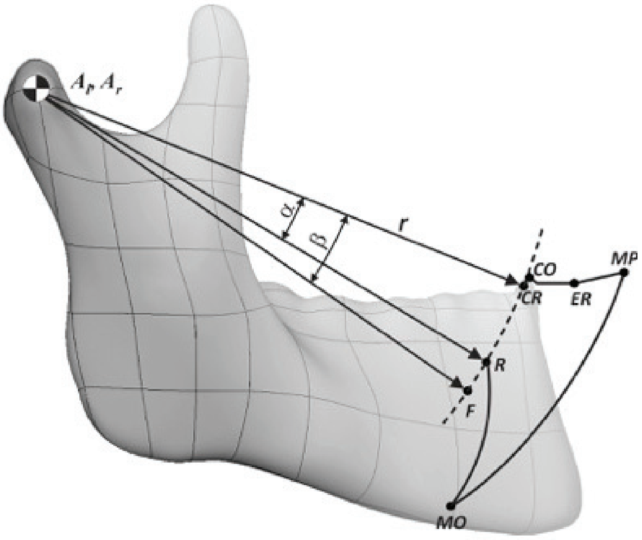
[1] – superscripts are explained in equations (1) and (2).

During symmetric biting off the food with incisors the chewing movement does not occur. At the time of biting off the displacement of the mandible is the sum of the hinge and sliding movements. Figure 2 provides a view of cross section of the mandible in the sagittal plane with the field of possible displacements of the incisor [21]. In *F*-*R*-*CR* segment, the incisor moves along an arc with a radius r with center at the points A_r, A_l (hinge axis) lying in the TMJ (Fig. 2), therefore in modeling of the biting off process the sliding movement of the mandible was not included.

In order to determine the values of the forces generated by the muscles lifting the mandible [1], during the biting off, the following general assumptions were made:

1. The biting off is symmetrical in terms of kinematics and dynamics.
2. The height of the bite (h_s) does not exceed 0.035 m.
3. In the experimental studies, the movement of the lower incisors in the testing machine took place along a straight line (Fig. 2).
4. Experimental determination of the characteristic of force–displacement ($F_s - \Delta h_s$) ended when $F_s = 0.1F_{s\max}$ – due to the inertia of the measuring head (Fig. 3).
5. Horizontal overlap (*HO*) and vertical overlap (*VO*) amounted to *HO* = *VO* = 0.002 m [14].
6. During the simulation, the head of the mandible performed rotational movements in the TMJ (the head of temporal joint did not change its position during the simulation) – the movement of the lower incisors took place along the arc *F*-*R*-*CR* (r = const., $\beta = 26°$ and it corresponds to the maximum height of the bite $h_s = 0.035$ m) (Fig. 2).
7. The model did not include: disc in the temporal joint, the joint capsule, the joint's internal and external ligaments, the tendons, the deep layer of the masseter and the lateral pterygoid [1], [20] – mainly due to its initial attachment (some of the fibers are attached to the capsule and the articular disc), its action (it lowers the mandible) and the arrangement of the fibers [1].

1. The forces F_{wl} and F_{wr} modeled the resultant vectors of the spatial system of muscular forces, consisting of 3 forces F_{ij}, in the medial pterygoid, temporal and masseter, for the left and right side, respectively [27].



CO – centric occulsion, ***CR*** – centric relation,
R – maximum opening with no change in radius (α=10°÷13° or 0.02 ÷ 0.025 m [21]),
F – maximum opening with no change in radius in this paper (r = 0.08 m, β = 26° or 0.035 m),
MO – maximum opening, ***MP*** – maximum protrusion,
ER – edge to edge position incisors

Fig. 2. Border movements recorded in the sagittal plane – prepared on the basis of [21]

2.1. Tests

Six foodstuffs (dark chocolate, fresh smoked sausage, an apple, carrots, a chocolate bar with caramel and peanuts, and rusks) representing five basic groups (12 samples in each group) of consumed food (acc. to GUS – Central Statistical Office of Poland) were prepared for tests. The foodstuffs had to be available in every grocery and could be eaten immediately after unpacking. Since the aim of the tests was not to determine typical mechanical properties (Young's modulus, Poisson's ratio, the elastic and/or plastic limit) it was assumed that the shape and size of the samples should correspond to the bites typical of the selected foodstuffs. Table 2 shows the mean heights of the food samples of the different foodstuffs.

Table 2. Mean height of bite of food

Foodstuff	h_s^1 [× 10^{-3} m]
Chocolate	5.5 ± 0.5
Sausage	30.0 ± 2.2
Apple	26.0 ± 1.5
Carrots	20.0 ± 2.5
Caramel chocolate bar	19.0 ± 1.3
Rusks	10.2 ± 1.3

^{1} – values are means ±SD.

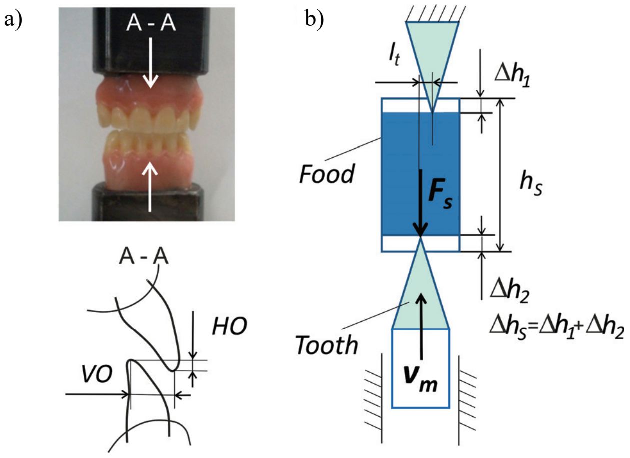


Fig. 3. Test holders:
(a) actual system, (b) general schematic

A special holder (Fig. 3) for determining the force-displacement characteristic ($F_s - \Delta h_s$) in conditions corresponding to biting off food was designed and made. Only the upper and lower incisors were included in the holder since the subject of the tests and the numerical simulations was solely biting off. The tests were carried out using an Instron (5944) testing machine. On the basis of [29] and for technical reasons the sliding velocity (v_m) of the upper holder was assumed to be constant and equal to $v_m = 0.025$ m/s.

$F_{s\max}$ and the corresponding maximum displacement ($\Delta h_{s\max}$) were determined from the $F_s - \Delta h_s$ characteristic, and a loading model for numerical simulations was developed.

2.2. Numerical simulations

2.2.1. Solid model of mandible and cranium

In the numerical calculations, solid models of the human skull and mandible, elaborated on the basis of the spatial geometry of a polyurethane model (Synbone), were used. Geometric model of the mandible has been developed in Geomagic program on the basis of scans of the mandible (Atos II – GOM mbH, Germany) and skull computed tomography images. The final version of the geometric model was prepared in the Ansys ver. 14.5 (Ansys, Inc., 2012, USA). The mass parameters (density) were adopted for the natural bone tissue [2]. In the model it was assumed that the solids are homogeneous in terms of the mechanical properties and continuous.

2.2.2. Structure of computational model of cranium-mandible kinematic system

After analyses of the structure of the human stomatognathic system a simplified model of the connection between the mandible and the cranium (in the form of two joints) was adopted [4], [12], [13], [18]. A kinematic diagram of such a mechanism is shown in Fig. 4. The system's driven link (the mandible) is connected with the base (the cranium) by means of two spherical hinges (kinematic pairs of class 3) modelling the temporal joints. Two kinematic excitations: q_l and q_r, in the form of symmetrically arranged linear drives forcing the displacement of the mandible relative to the cranium, were used in the cranium-mandible mechanism. The excitations model the elongation and contraction of the muscles moving the mandible. Active forces F_{wl} and F_{wr} in excitations q_l and q_r represent the resultant forces of the muscles (masseter, medial pterygoid and temporal) situated on respectively the left and right side of the mandible. The mass parameters of the created model members are those of the natural bone.

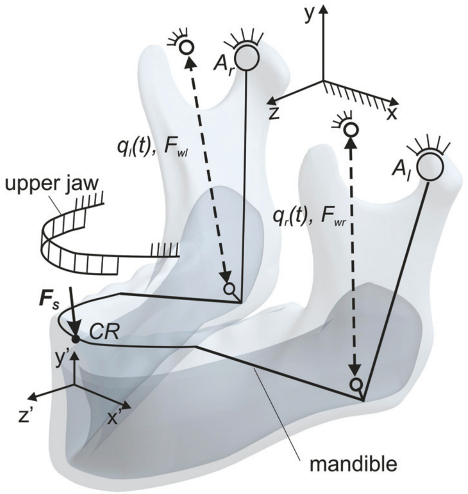


Fig. 4. Kinematic scheme of human cranium-mandible system, where *xyz* global coordinate system and *x*′*y*′*z*′

2.2.3. Simulation studies of biting off food model

In the simulations the mandible would be moved from the lower position until the upper and lower teeth touched (clenched). A general scheme of following stages of simulation is presented in Fig. 5. Height h_z stands for the distance between the upper and lower incisors. If $h_z > 0$, the mouth was open, and if $h_z = 0$, the mouth was closed. In the course of closing the mouth, when h_z was larger than h_s, the incisors were not in contact with the food; only when $h_z \leq h_s$, contact appeared and biting off would begin.

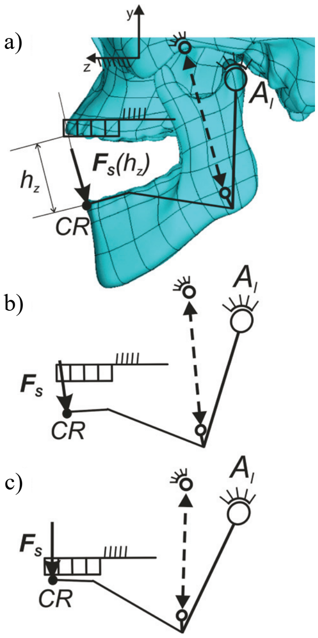


Fig. 5. View of the system computing model: (a) solid model, (b), (c) diagram of stages of simulation with vector of force F_s and height h_z being shown

The value of force F_S pointed in *CR* (Fig. 5) as a function of height h_z is described by the formula

$$\begin{cases} F_s = 0, \quad \text{for } h_z > h_s, \\ F_s = F_s(\Delta h_s), \quad \Delta h_s = h_s - h_z, \quad \text{for } h_z \leq h_s, \\ F_s = F_{s\max}, \quad \text{for } h_z = h_{s\max}. \end{cases} \tag{3}$$

The initial position of the mandible relative to the cranium (at time $t = 0$ s) was the same for each of the biting off simulations (Fig. 5a). The incisors were positioned at a distance $h_z = 0.035$ m from each other. During the simulation of biting off food the incisors would move at constant velocity $v_m = 0.025$ m/s.

A (created and described) parametric model of the food being bitten off as a function of force F_S (Figs. 4 and 5) was placed between the teeth in the cranium-mandible system. By changing the geometric and elastodamping parameters of the food model wide groups of foodstuffs being crushed, particularly the set of foodstuffs whose parameters were determined on the basis of the experimental results presented in the previous section, could be easily described.

The solid computational model was used to run numerical dynamic simulations of biting off in the LMS DADS computer system for the dynamic analysis of multi-link systems [8].

3. Results

Based on the experimental studies the characteristics ($F_s - \Delta h_s$) of foodstuffs were determined, on the basis of which loading models of the mandible, individually for each food product, were developed. Loading models were used for modelling of the bitten off food during the numerical simulation. Figure 6 shows diagrams $F_s - \Delta h_s$ for foodstuffs (6a÷6f) and their corresponding loading models (6g÷6l), whereas the values of forces $F_{s\max}$ and displacements $\Delta h_{s\max}$ were taken from the diagrams and given in Table 3.

Table 3. Mean maximum loads and corresponding mean maximum displacements for particular foodstuffs

Foodstuff	$F^1_{s\max}$ [N]	$\Delta h^1_{s\max}$ [× 10^{-3} m]
Chocolate	84.7 ± 7.2	4.5 ± 0.1
Sausage	59.7 ± 9.5	18.2 ± 2.3
Apple	36.0 ± 10.0	5.8 ± 2.6
Carrots	114.1 ± 25.8	10.5 ± 1.9
Chocolate bar	48.1 ± 6.5	3.1 ± 0.3
Rusks	27.7 ± 15.0	2.8 ± 0.9

[1] – Values are means ±SD.

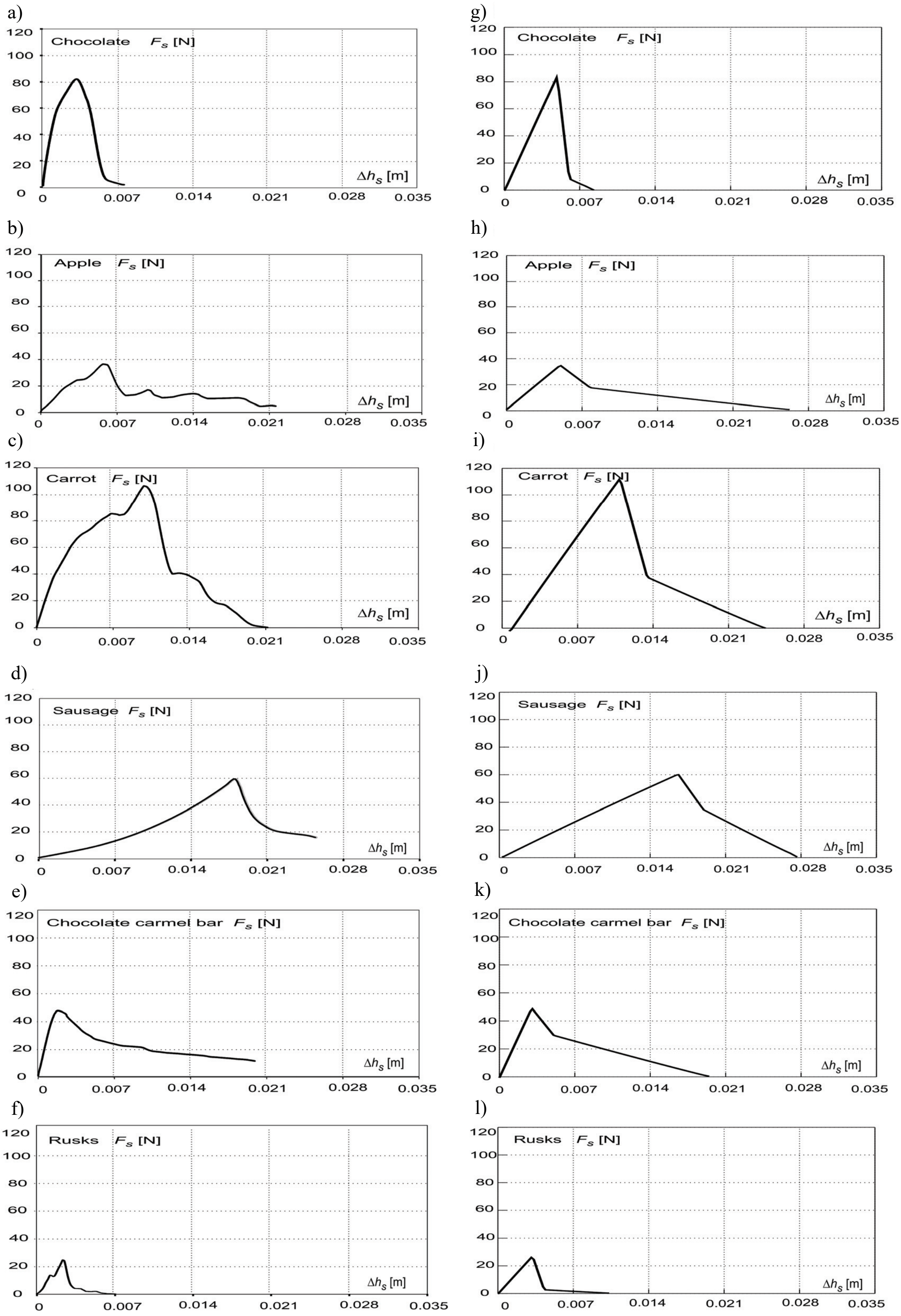


Fig. 6. $F_s - \Delta h_s$ characteristics: (a) dark chocolate, (b) apple, (c) carrots, (d) fresh smoked sausage, (e) chocolate bar with caramel and peanuts, (f) rusks and corresponding loading models (g), (h), (i), (j), (k) and (l)

The simulations yielded results in the form of active forces F_{wl} and F_{wr} which are presented as a function of parameter h_z in Fig. 7. Owing to the symmetry (in the median plane) of the cranium-mandible system, the values of F_{wl} and F_{wr} were identical and so only changes in force F_{wl} are shown in the diagrams.

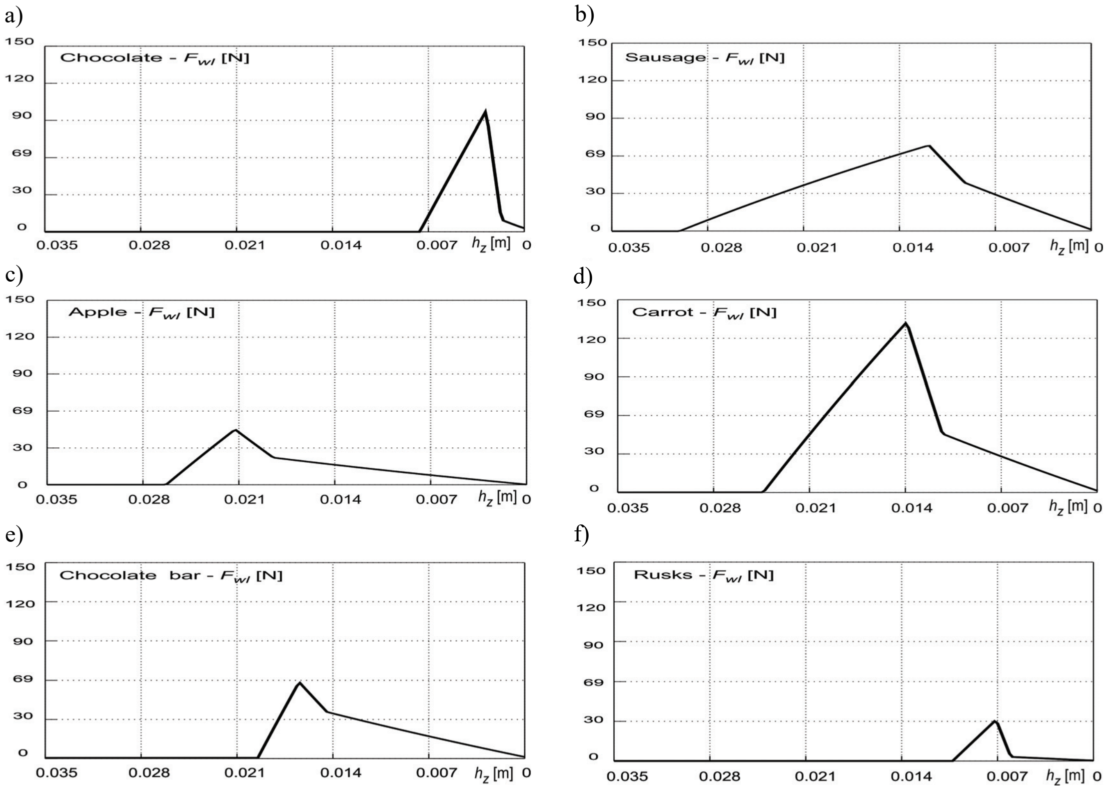


Fig. 7. Diagram of forces F_{wl} in muscle during simulations of occlusion as a function of distance h_z between teeth: (a) chocolate, (b) sausage, (c) apple, (d) carrot, (e) chocolate caramel bar and (f) rusks

Table 4. F_{ij}^1 and F_{ijk}^1 as a function of food being bitten off for selected muscles

Name of Muscles	Side	Forces N	Foodstuff					
			Chocolate	Sausage	Apple	Carrots	Chocolate bar	Rusks
Masseter	Left	F_{ml}	63.3	48.1	28.1	89.4	38.1	21.1
		F_{mlx}	–9.6	–7.3	–4.3	–13.6	–5.8	–3.2
		F_{mly}	57.8	43.9	25.6	81.6	34.8	19.2
		F_{mlz}	22.7	17.3	10.1	32.1	13.7	7.6
	Right	F_{mr}	60.8	46.2	27.0	85.9	36.6	20.2
		F_{mrx}	8.6	6.5	3.8	12.1	5.1	2.8
		F_{mry}	55.8	42.4	24.8	78.8	33.6	18.6
		F_{mrz}	22.6	17.2	10.0	32.0	13.6	7.5
Medial pterygoid	Left	F_{pl}	21.8	16.6	9.7	30.9	13.1	7.3
		F_{plx}	9.7	7.4	4.3	13.7	5.8	3.2
		F_{ply}	22.8	17.3	10.1	32.2	13.7	7.6
		F_{plz}	0.9	0.7	0.4	1.2	0.5	0.3
	Right	F_{pr}	24.5	18.6	10.9	34.6	14.7	8.1
		F_{prx}	–10.6	–8.1	–4.7	–15.0	–6.4	–3.5
		F_{pry}	25.8	19.6	11.4	36.4	15.5	8.6
		F_{prz}	1.3	1.0	0.6	1.8	0.8	0.4
Temporal	Left	F_{tl}	15.4	11.7	6.8	21.7	9.2	5.1
		F_{tlx}	–4.6	–3.5	–2.1	–6.6	–2.8	–1.5
		F_{tly}	9.6	7.3	4.3	13.6	5.8	3.2
		F_{tlz}	–10.7	–8.1	–4.7	–15.1	–6.4	–3.6
	Right	F_{tr}	11.0	8.4	4.9	15.6	6.6	3.7
		F_{trx}	3.2	2.5	1.4	4.6	1.9	1.1
		F_{try}	8.0	6.1	3.5	11.3	4.8	2.7
		F_{trz}	–9.0	–6.9	–4.0	–12.8	–5.4	–3.0

[1] – superscripts are explained in equations (1) and (2).

F_{ij} and F_{ijk} as a function of the food being bitten off for the particular muscles (Table 4) were determined on the basis of formulas (1) and (2), and F_{wl} and F_{wr}.

On the basis of equations (1) and (2), the coefficients $C_{m(ijk)}$ (Table 1) and the results of experimental studies (Table 3), as well as the numerical simulations, the functions between muscular force F_{ij} and foodstuff were determined. Equations for muscles (masseter (4), medial pterogoid (5), temporal (6)) are described by the formulas

$$\begin{aligned} F_{ml} &= 0.76F_{s\max} + 0.64, \\ F_{mr} &= 0.74F_{s\max} + 0.43, \end{aligned} \tag{4}$$

$$\begin{aligned} F_{pl} &= 0.30F_{s\max} + 0.22, \\ F_{pr} &= 0.27F_{s\max} + 0.13, \end{aligned} \tag{5}$$

$$\begin{aligned} F_{tl} &= 0.19F_{s\max} + 0.04, \\ F_{tr} &= 0.13F_{s\max} + 0.20. \end{aligned} \tag{6}$$

Characteristics of dependences and values of square deviation (R^2) were presented in diagrams (Fig. 8).

4. Discussion

The most important result of work are the equations (Fig. 8) presenting the dependences between the muscular force F_{ij} and the food product. The dependence enables, on the basis of the knowledge of $F_{s\max}$, determining the forces in the individual muscles (masseter, medial pterygoid, temporal) on the left and right side (Fig. 8). The advantages of the proposed equations may include decoupling F_{ij} from the majority of individual features, among others, EMG, dental health, muscular effort, age and furthermore, the developed equations are functions of one variable. The only individually varying parameter considered in the proposed equations was the geometry of the mandible (geometric model of the mandible was based on the Synbone company's model), which may have influence on the results. The limitations of presented equations may include the scope of usage only to biting off products whose $F_{s\max}$ does not exceed 120 N, despite the fact that the equations are linear.

A detailed analysis of the known empirical equations [7], [24] has shown that the value of muscular force is dependent on three parameters EMG, PCS and on a constant (k) determined for the skeletal muscles – after Weijs [30] k is independent of gender, age and muscles.

In the literature, a lot of publications on the chewing process can be found, but these are works that focus mainly on kinematics and dynamics, changes in the texture of food, activity and preparation of bolus [5], [6], [9], [23]. Furthermore, mastification is a form of compressing (crushing, squashing) foodstuff, which additionally is moistened with saliva [9] and transported from the left dental arch to the right one [15], until a bolus of food is prepared. During chewing the foodstuff is loaded cyclically 25÷45 times before it is ready to be swallowed [9], and its mechanical properties change with each cycle [10]. Whereas, biting off is an example of shearing where the food begins to lose its cohesion under the pressure (crushing) of the incisors, exerted on a very small area and only in the very end of this process the actual shearing takes place. Moreover, during biting off there is no moistening of food with saliva and biting off is only one cycle, therefore there are no changes in mechanical properties of food.

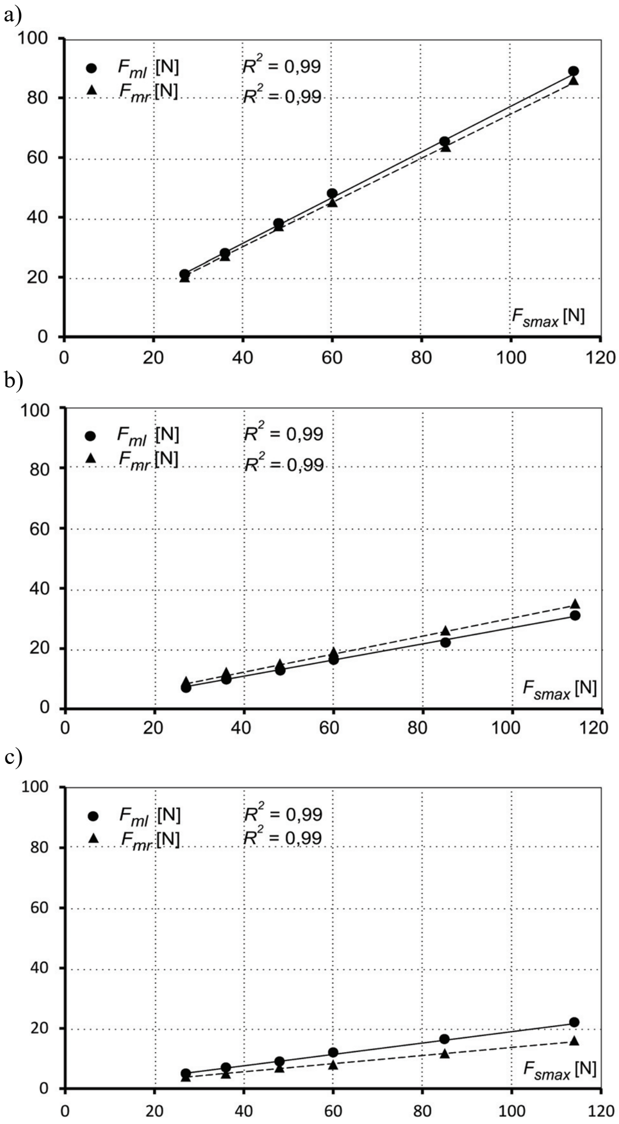


Fig. 8. Diagram of dependences between F_{ij} and $F_{s\max}$ for each of the muscles: (a) masseter, (b) medial pterogoid, (c) temporal

On the basis of the aforementioned differences, there are no substantial grounds for conducting a comparison of the results of biting off with chewing.

In [26], values of muscular forces for the case corresponding to the loading of the incisors, but with dividing the muscles into areas, were given. In spite of this, it turned out that the values of forces F_{ml}, F_{mr} (masseter), F_{tl} and F_{tr} (temporal) are comparable, while the value of F_{pl} and F_{pr} (medial pterygoid) was as much as 4.6 times higher than the values given in [26]. The comparison was made for the largest values of muscular forces obtained for carrots.

On the basis of experimental studies, such position of the mandible can be determined (i.e., the angle α or the distance between the teeth h_z) where the muscles reach the maximum values of F_{ij} during biting off a bite of food.

Analysis of the data presented in Fig. 6 showed that each product has a different characteristic of $F_s - \Delta h_s$ depending, among others, on the ingredients, method of preparation (chocolate, sausage, rusk, candy bar) and vegetation conditions (apple, carrot). On the basis of knowledge of the values h_s (Table 2) and $\Delta h_{s\max}$ (Table 3) one can determine, during biting off a bite of food, the position of the mandible in relation to the upper jaw (the distance between the incisors) in which the mandible is the most loaded. During biting off the largest loads of the mandible occur in the position at which its distance in relation to the upper jaw is equal to 0.004÷0.022 m.

Referring the outcomes of the studies conducted to the results presented in [3], the value of the determined maximum force $F_{s\max}$ = 114.1 N (carrot – Table 3) is lower by as much as 54.4% from the maximum occlusion force measured experimentally on the incisors. This indicates that the chewing muscles can generate the values of F_{ij} exceeding the value of $F_{s\max}$. For confirmation of the above thesis, Table 5 compares values of F_{ij} as a function of the food product with the values of the maximum muscular forces ($F_{ij\max}$) determined on the basis of the largest occlusion force [27]. According to Engelen et al. [6] to reach a yield point (during crushing) of such foodstuffs as: breakfast cake, melba toast, cheese, peanut and carrot, the muscular system must generate the occlusion force equal to 1.7÷53.0 N, while under laboratory conditions it can generate the occlusion force up to 750 N on the molars and 250 N on the incisors [3].

As mentioned in the introduction the results may be useful as indicators of the level of loads of the mandible while biting off food not only for biomechanics engineers, but also for the doctors caring for patients after surgical procedures connected with the mandible. In order to exploit the results, one should in the future verify the assumptions made, the numerical model and perform additional studies and calculations associated also with chewing of various foodstuffs. In the next stages of research on stomatognathic system it is planned to extend the model with additional degrees of freedom (enabling the major movements in the temporal joint to be modelled – above all the rotation and the displacements) and forces simulating the work of individual muscles.

5. Conclusions

1. The equations enabling calculation of forces in the individual muscles, on the basis of the knowledge of foodstuff's breaking force, were determined.
2. In the physiological conditions, during biting off the strongest occlusion forces and/or muscular forces correspond to the food breaking force.
3. The position of the mandible, corresponding to the heaviest load during biting off, is the function of the food.

Table 5. Muscular forces (F_{ij})[1] and maximum muscular forces ($F_{ij\max}$)[2]

Muscles	Side	F_{ij} [N]	Foodstuff[3]						$F_{ij\max}$ [N]
			1	2	3	4	5	6	
Masseter	Left	F_{ml}	63.3	48.1	28.1	89.4	38.1	21.1	161.0
	Right	F_{mr}	60.8	46.2	27.0	85.9	36.6	20.2	155.0
Medial pterygoid	Left	F_{pl}	21.8	16.6	9.7	30.9	13.1	7.3	64.0
	Right	F_{pr}	24.5	18.6	10.9	34.6	14.7	8.1	71.0
Temporal	Left	F_{tl}	15.4	11.7	6.8	21.7	9.2	5.1	39.0
	Right	F_{tr}	11.0	8.4	4.9	15.6	6.6	3.7	32.0

[1] – muscular forces as function of $F_{s\max}$ of selected foodstuff,

[2] – maximum muscular forces determined through numerical analysis [17],

[3] – 1 dark chocolate; 2 sausage; 3 apple; 4 carrots; 5 chocolate bar; 6 rusks.

4. The values of the forces in the muscles and the models of the distribution of the resultant forces among the component muscles, correctly model the system of forces in the muscles.
5. Weaker occlusion forces are needed to bite off today's foodstuffs than the forces which the mastication muscles are capable of generating.

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