

Dental tribology: a systems approach

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Purpose: This article presents the new system approach for the biotribological description of the stomatognathic system, with particular emphasis on one of its subsystems, the dental organ. *Methods:* The peculiarity of the dental organ is emphasised, associated with a specific autonomic environment, next to the external environment, resulting from the impact of the organism on the dental organ. The autonomic environment increases the number of relations between elements in the dental organ and hinders its examination. *Results:* The characteristics of the dental organ are described. Its main elements, their properties, and the relationships between them are identified, and the system's functions, inputs and outputs are presented. The systems approach addresses these difficulties, enabling the analysis of the dental organ and its tribological characteristics. *Conclusions:* The dental organ has an "autonomic" environment, which significantly increases the number of tribological relationships and complicates their analysis. Knowledge of the tribological attributes of the dental organ can be useful in studying detailed aspects of the function of the dental organ. The specific features of the analysed system and the uniqueness of its structure necessitate the use of appropriate methodology for testing the tribological properties.

Key words: stomatognathic system, wear, friction, system approach

1. System approach for analysis of tribological processes

Ludwik von Bertalanffy's work on system analysis (particularly his general systems theory [1]) was a significant impetus for the development of numerous modern fields of science. The new approach (paradigm) to scientific issues, which enables a comprehensive analysis of the behaviour of the research objects, has yielded a number of interesting results in various fields, e.g., physics, chemistry, biology, psychology, sociology, and literature [2]. As stated by Bertalanffy [1], the essence of the system paradigm is "the whole is more than the sum of its parts". This implies a holistic perception of objects and processes as the research subjects, in contrast to the classical Cartesian principle, according to which the whole can be broken down into parts and the behaviour of the entity can be judged by analysing the parts separately.

The analytical (reductionist, mechanistic) approach yields good results in conceptual systems (such as mathematical systems) wherein relationships between the elements do not exist or are weak. These conditions are not satisfied by systems consisting of elements with strong interactions, which are usually nonlinear. Additional complications in the use of the classical approach arise in the case of open systems, i.e., those that exchange matter, energy, and information with the environment. Thus, the need for a new approach for analysing the research problems of modern tribology has been evident for some time.

The tribological community adopted the ideas proposed by Bertalanffy relatively early, and a system analysis of tribological phenomena was performed by Czichos [3], who defined the tribological system as a set of structurally and functionally related elements. To describe the tribological system, it is necessary to specify its structure, function (technical purpose), and input–output relationships. The concept of structure, which is widely used in science, does not have a uni-

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form connotation and is defined differently in different fields. In mathematics, the term “structure” is mainly understood as the relationship between elements in a system, assuming that the nature (properties) of the elements does not play a significant role. A similar approach is employed in physical sciences, where the concept of system structure includes the way in which elements are organised along with the relationships between these elements [4]. Structures are divided into two classes: equilibrium and dissipative [5]. Equilibrium structures arise during reversible changes caused by slight deviations from the state of thermodynamic equilibrium. An example is the crystal structure. In contrast, dissipative structures arise as a result of the exchange of matter and energy between the system and the environment in the case of a significant deviation from thermodynamic equilibrium. Benard cells are common examples of such structures.

According to Czichos, the structure of the tribological system is determined by its elements (A), the properties of the elements (P), and the relationships between the elements (R). Thus, it can be expressed as the following set:

$$S = \{A, P, R\}. \quad (1)$$

Tribological systems are open systems, i.e., they exchange matter, energy, information with the environment. The flows directed from the environment to the system are associated with the inputs $\{X\}$, and those directed from the system to the environment are associated with the outputs $\{Y\}$. The inputs and outputs may take the form of specific physical quantities (parameters), which Czichos denoted as primary variables (e.g., strength, dimension), or defined more generally (work, movement, heat, mass).

There is a specific relationship between the $\{X\}$ and the $\{Y\}$ resulting from the implementation of the system function (objective function). In the tribological system, an operator $\{T\}$ transforms the inputs $\{X\}$ into the outputs $\{Y\}$. The system function can be set according to the system state [6]:

1. Dynamic state: the outputs and inputs change over time. This state can be described by a system of differential equations called motion equations;
2. Steady state: in some cases, the system may be in dynamic equilibrium; otherwise, it is in the steady state. The outputs $\{Y\}$ are related to the inputs $\{X\}$ by a linear function;
3. State in the presence of stochastic processes: random processes occur; probabilistic principles are used to describe the behaviour of the system.

The most general schematic of the tribological system is usually presented in the form of a black

box (Fig. 1). Sometimes, this pattern includes disturbances and losses [7]. However, both the disturbances and losses contribute to the streams of matter, energy, and information resulting from the functions of the system, thus, constituting a part of them. They are distinguished by the fact that this is not a contribution resulting from the implementation of the functions of the system, resulting in a negative impact on the system. It appears to be reasonable to classify outputs and inputs as controlled or uncontrolled [8].

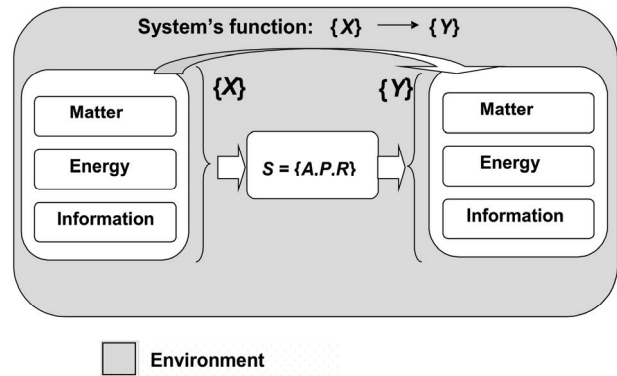


Fig. 1. General schematic of the tribological system in the form of a black box ($\{X\}$ and $\{Y\}$ represent the system inputs and outputs, respectively)

The diagram presented in Fig. 1 refers mainly to engineering tribological systems. Tribological systems in the field of biology (biotribological systems) differ significantly from engineering tribological systems and, therefore, require a different research methodology. In particular, there is an urgent need to develop rules for inferring the behaviour of biotribological systems in their natural environment (*in vivo*) according to the results of research performed under extracorporeal conditions (*in vitro*). This is one of the fundamental challenges of modern biotribology.

The objective of the present study was to investigate the substantial issues of dental biotribology from the general systems theory point of view.

2. Stomatognathic system from viewpoint of general systems theory

The stomatognathic system (masticatory system) is the musculoskeletal system of the head, neck, and shoulder girdle. It is characterised by a functional and

morphological relationship between the elements which exhibit mutual innervation and vascularisation. From a tribological perspective, the system has two main subsystems: the dental organ and the temporomandibular joint. Elements of the dental organ (individual teeth) are permanently embedded in the mandible and maxilla which move together and are connected by the temporomandibular joint (Fig. 2).

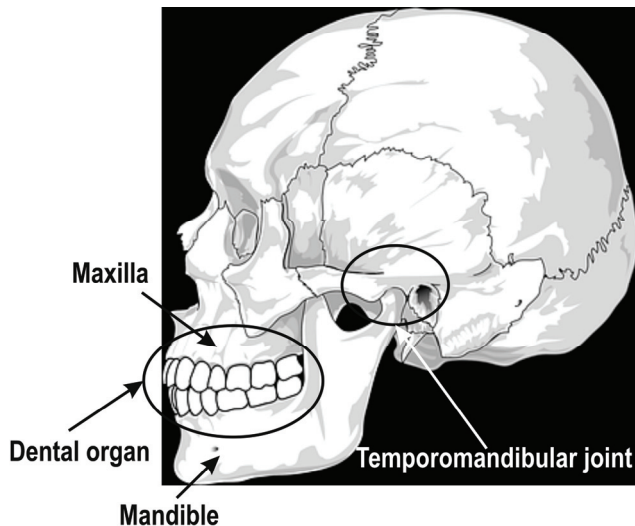


Fig. 2. Stomatognathic system (without soft structures)

In technical terms, the mandible is hinged in the maxilla and acts as a first-class lever, activated by a complex system of single-acting actuators (muscles). In systemic terms, the dental organ and temporomandibular joint can be treated as two tribological systems functionally linked with each other by a group of muscles. Both systems exhibit mutual interaction, which is particularly important in the case of abnormalities within the dental organ. Improper occlusal conditions, e.g., caused by excessive tooth wear, can significantly disrupt the function of the temporomandibular joints [9]. However, in the literature, there is no clear view on this issue, because studies have indicated that excessive tooth wear, e.g., caused by bruxism¹ [10], does not cause temporomandibular joint dysfunction.

Tribological interactions also occur between the teeth and the tongue, within the stomatognathic system. In the present study, it was assumed that these interactions – although they play an important role in the formation of the biofilm on the tooth surface – they do not play a significant role in the tribological function of the dental organ.

¹ Bruxism: involuntary habitual grinding of the teeth, mostly during sleep.

Comparison of a dental organ with a technical tribological system can reveal important differences. The differences are due to the two streams of energy, matter and information flows in the dental organ. In addition to the flows from the surrounding environment, the body provides flows within which the dental organ functions. In contrast to the classical **external environment**, we are dealing with a second type of environment, which has been described as an **autonomic environment** [11]. In Figure 3, a schematic of the biotribological system is presented. The proposed scheme applies to all biotribological systems, including joints, i.e., systems where it is necessary to have an autonomous environment associated with the living body.

One consequence of an autonomous environment is additional feedback. Biotribological systems are subjected to interactions resulting from homeostasis, i.e., the organism's desire to maintain its internal balance. According to Bertalanffy [1], the feedback model associated with homeostasis explains the secondary regulation, i.e., regulation by means of pre-established mechanisms and routes, while the regulation resulting from the openness of the system is the "primary regulation" associated with the dynamic balance of processes. This creates methodological difficulties in the study of biotribological systems where the two regulations interweave. Information flows play a decisive role in secondary regulation because homeostasis is considered to be "open" to incoming information and "closed" to mass and energy [3].

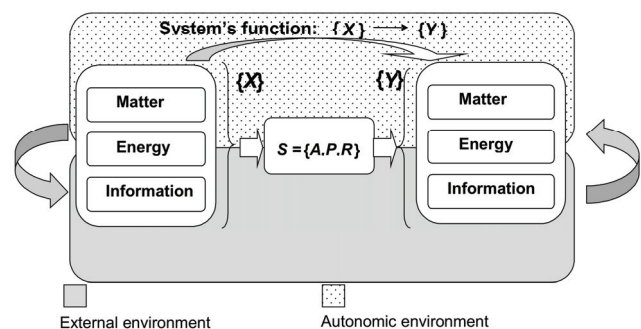


Fig. 3. General schematic of the biotribological system in the form of a black box ($\{X\}$ and $\{Y\}$ represent the system inputs and outputs, respectively)

The introduction of two separate environments into the model of the stomatognathic system is a conceptual procedure because, in reality, there is no physical boundary between these environments. An example of an overlap between the two environments is the body's response to odour stimuli, i.e., when information from the external environment causes increased work of the

salivary glands (autonomic environment reaction in the form of increased salivation) and changes in the environment inside the mouth. The transport of ions from the autonomous environment to the outer layer of the teeth (enamel) plays an important role in maintaining their favourable tribological properties.

Another manifestation of the mutual interaction of the two environments is the phenomenon of reparation, which involves the formation of dentin at the pulp site in places where excessive wear of the outer layer of the tooth (enamel) occurs [12], [13]. Increased enamel wear due to an excessive amount of hard particles in food (abrasive wear), intensive brushing or carious defects reduces the thickness of the enamel deck. Information regarding the increased wear, which probably results from the increased mechanical susceptibility of the enamel or the shortening of the path of heat stimuli, reaches the autonomous environment, causing the deposition of tertiary dentine [12].

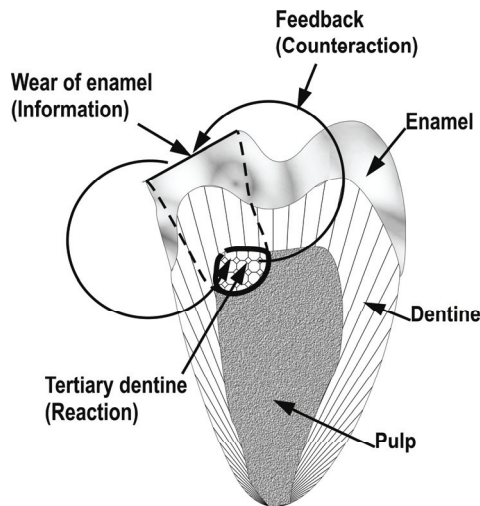


Fig. 4. Schematic of reparation (description in the text)

In the case of the reparation phenomenon, in accordance with the Le Chatelier principle (defying rule), if the system in equilibrium is subjected to external stimuli that disturb this balance, changes occur in the system, diminishing the impact of these stimuli. According to the Le Chatelier principle, the self-organising tribological systems are characterised by the emergence of dissipative (secondary) structures [5]. The phenomenon of **reparation** is a different (surrogate) mechanism from regeneration, which is only possible in the presence of live cells. In the process of enamel growth, enamel-forming cells (ameloblasts) undergo apoptosis², resulting in the formation of a hard miner-

² Apoptosis: programmed cell death for the good of the whole organism.

alised substance. Mature enamel does not contain live cells, thus, it cannot regenerate after being used. The reparation schematic is shown in Fig. 4.

The mature stomatognathic system can be treated as a complex adaptive system where tissues are subjected to genetic, epigenetic, and environmental influences at different levels with varying degrees of intensity and durations [13]. According to the authors of this publication, the system approach for the description of craniofacial growth and development has “many positive outcomes, including an appreciation of the overview of the interactions that occur within sub-networks in the mature stomatognathic system” [13].

3. Function of stomatognathic system

The basic function of the stomatognathic system is to collect and prepare food for digestion. The implementation of this function is possible owing to a specific force-movement field resulting from the operation of the muscular system and the temporomandibular joint. This joint is the only one in the body that has an articular disc, which enables complex jaw movements and thus, the effective grinding and chewing of food [14]. Control signals are transmitted to the system from the central nervous system and so are responses to the entire complex of proprioceptive and exteroceptive³ parameters. The dental organ also performs other functions, e.g., it participates in speech. However, these functions are beyond the scope of the present work.

Using the analogy to engineering systems, the functions of the biotribological systems of the stomatognathic system can be presented in the manner proposed by Czichos [3] (Table 1).

In accordance with the work of Czichos, it should be assumed that the “functional” description of the system is “external” because it refers to the system’s relationship with the environment (in this case, external environment). Thus, owing to the randomness of the changes in the external environment, real implementations of the functions of the dental organ are of a stochastic nature. This is mainly due to the wide variety of food consumed, which is characterised by various chemical, physical, and mechanical properties

³ Proprioceptors: receptors located in the muscles, tendons, joints, and periosteum which transmit signals to the central nervous system about the loads and locations of the elements of the musculoskeletal system. Exteroceptors: sensory organs receiving stimuli from the external environment.

Table 1. Functions of biotribological systems of the stomatognathic system

System name	Inputs and outputs necessary to perform the system functions		Main function of the system
	Main inputs	Main outputs	
Temporomandibular joint	Movement + work	Movement	Implementation of directed movement
		Work	Power transfer
Dental organ	Movement + work + materials	Materials	Formation of materials

[15], [16]. Additionally, real implementations of the functions of the dental organ depend on the psychological conditions psychological conditions. Parafuncions, including bruxism, play an important role here [17].

In the literature, the physiological function of the dental organ is presented in the form of a chewing cycle. There are a few descriptions of the chewing cycle that differ slightly [18], [19]. However, for the purposes of this study, the description can be limited to two tribologically important phases (Fig. 5) [20]. During phase I (closing phase), the teeth enter into mutual contact (occlusion). During phase II (opening phase), the surfaces of the opposing teeth are completely separated. During phase I, the food is subjected to compression, crushing, and abrasion (grinding), which occur with direct or indirect (tooth–bolus–tooth) contact of the tooth surfaces. The comminution process is preceded by complex mandible movements (phase I) which vary widely according to the type of food being chewed. In contrast, the mandible movements during phase II are closely related to the surface formation of the occlusal teeth (molars). The posterior upper and lower teeth of mammals, which are called tribosphenic molars, have a complex system of cusps and fossa, and are subjected to a dynamic adjustment (running in) process [21]. A simplified schematic of the chewing cycle is shown in Fig. 5.

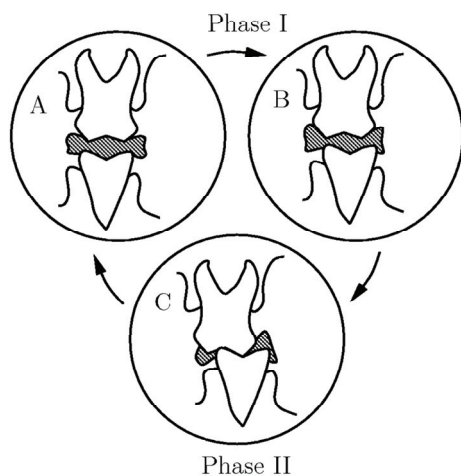


Fig. 5. Simplified schematic of the chewing cycle (reproduced with permission from ref. [20])

4. Structure of dental organ

The structure of the human dental organ changes throughout life, and the most visible example of this is the occurrence of two types of dentition: primary and permanent. The teeth form two “dental arches”, each having 10 and 16 teeth in primary and permanent dentition, respectively. Primary teeth erupt in childhood, starting from 4–6 months of age, and fall out between 6 and 13 years of age. They are replaced by permanent teeth. The last teeth (wisdom teeth) erupt between 17 and 20 years of age, although they sometimes do not erupt at all. Depending on the position in the dental arch, teeth differ in their shape and role in grinding food. Additionally, they have different names. In each of the dental arches of permanent dentition, there are four incisors, two canines, four premolars, and six molars (Fig. 6).

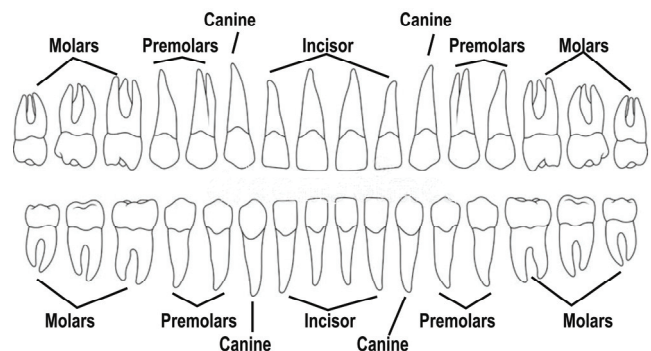


Fig. 6. Expanded view of human permanent dentition

Each jaw tooth has an opposite mandibular tooth. The contact between opposing teeth is complex, because with the jaws closed, each tooth contacts two teeth of the opposite mandible. Additionally, the contact conditions of the opposing teeth change with age, mainly owing to the physiological wear of the teeth and a reduction in their height, particularly for molars and premolars. This also implies a significant change in the biomechanics of the function of the dental organ.

A single tooth has a complex, hierarchical structure, the details of which are sometimes visible only

under high magnification. A mature (permanent) tooth consists of a crown, a neck, and 1–3 roots (Fig. 7). Inside is the tooth cavity, which is called the chamber. The tooth cavity is filled with vascularised and innervated pulp. The pulp is surrounded by hard tissue (dentin), which is covered by the outermost layer of the tooth (enamel). Owing to the direct participation of enamel in tribological processes, it should be considered as the most important element of the biotribological system.

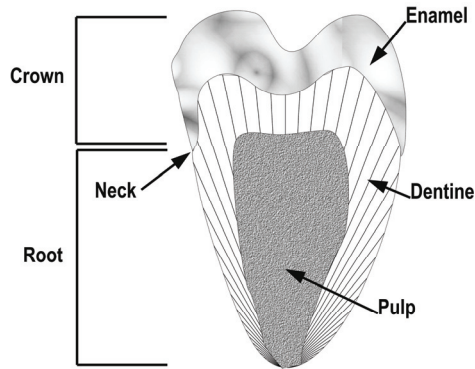


Fig. 7. Cross-section of a tooth

The main enamel component, which, according to various sources, accounts for 96–97% of its total weight, is an inorganic substance containing mainly hydroxy-

apatite (with the chemical formula $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$) and small amounts of calcium carbonate, calcium fluoride, magnesium phosphate, and other salts [22]. F ions can replace hydroxyl ions in the enamel, resulting in the conversion of hydroxyapatite into fluorapatite. It is believed that fluorapatite crystals are more resistant to acids than hydroxyapatite crystals, which implies a greater resistance to caries [23]. The hydroxyapatite in the enamel (biological hydroxyapatite) has a different stoichiometric Ca/P ratio (usually <1.60) from an ideal crystal (1.67) [24].

The organic substance, which accounts for approximately 1% of the total weight of mature enamel, consists of soluble and insoluble proteins (mainly enamelin). The remainder of the enamel consists of mineral and organic substances, along with water [24].

The basic structural unit of tooth enamel is the prism. This name, which was introduced by Retzius at the end of the 19th century, refers to elongated formations closely arranged side-by-side in glaze layers, having a cross-sectional thickness of 4–7 μm [25]. Enamel prisms are made of hydroxyapatite crystals that crystallise in the hexagonal system. Typical rod crystals in mature enamel are with width of 60–70 nm and thickness of 25–30 nm [26]. Their arrangement inside a single prism is not random exhibits regularity (Fig. 8). According to the dominant view, neighbouring

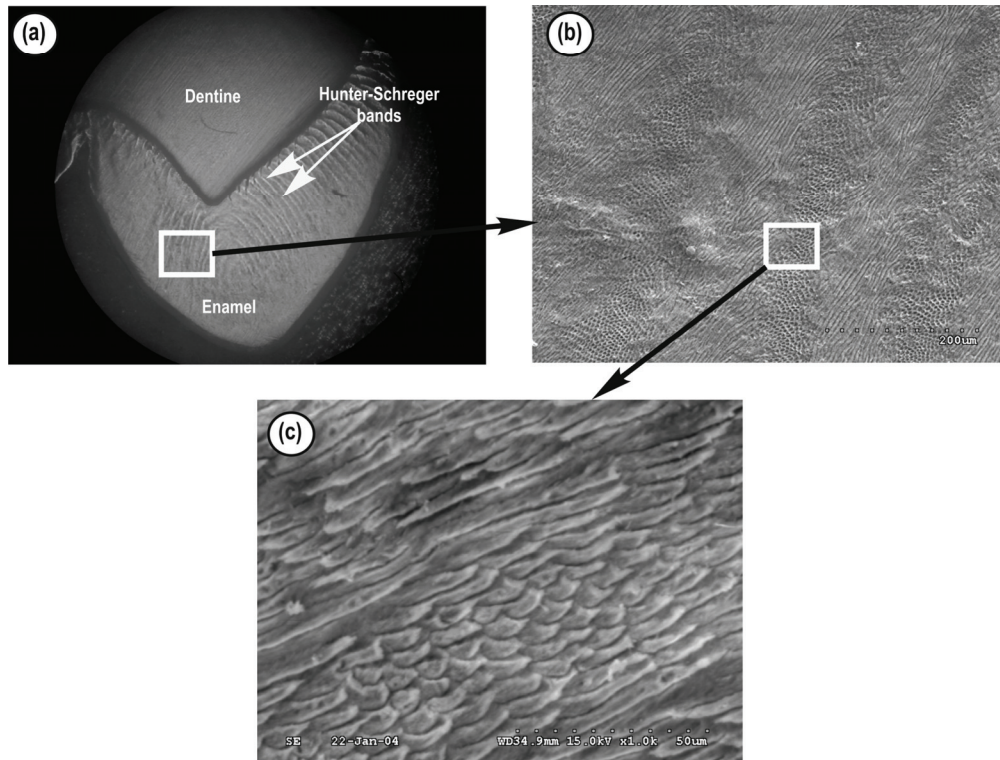


Fig. 8. Hierarchical structure of human tooth enamel, observed at different magnifications: (a) optical microscope, 20 \times ; (b) scanning electron microscope (SEM), 200 \times ; (c) SEM, 1000 \times (visible prisms (keyholes) with orientations parallel and perpendicular to the cross-sectional plane)

prisms are connected by a thin layer of interprismatic substance. Prisms usually have the cross-sectional shape of a “keyhole” and are sometimes more oval-shaped or arched. The development of enamel occurs from enamel-forming cells (ameloblasts) and begins in the foetal stage. This process has unique dynamics, and the periodicity of the enamel deposition and mineralisation can be observed in a microscopic image in the form of the Retzius lines resembling rings in the longitudinal section of the tree. Enamel prisms do not run individually but combine into bands with alternating orientations. In an optical microscope, these bands provide an image of darker and lighter lines called Hunter–Schreger lines. The structural details of enamel are shown in Fig. 8.

Enamel is a highly nonhomogeneous material with regard to its structural features and properties. The course of prisms in the enamel board is complex, which varies depending on the location under observation. Generally, prisms are arranged radially in relation to the enamel surface, and most of them have a wavy or spiral arrangement. Some of them twist around their axes. It is believed that most of the surface enamel layer (approximately 20–80 nm thick) does not contain prisms, thus, it is called non-prismatic enamel [26]. The chemical composition differs among the various layers of enamel. According to the extensive research of Cuy et al. [27], the chemicals in enamel are converted into oxides, as follows: the concentrations of CaO and P₂O₅ are higher in the enamel surface layer than in the deeper layers (this also applies to Cl), while the concentrations of Na₂O and

MgO are higher near the dentine than in the surface enamel. A gradient of the enamel hardness towards dentine is observed [27]–[29].

5. Dental organ: elements, properties, and relations

Tooth enamel plays a decisive role in ensuring the durability and reliability of not only the dental organ but also the entire stomatognathic system, making it a key element. Thus, research on the unique properties of enamel is important. Owing to the heterogeneity of enamel, there are methodological problems in the study of its properties, which are mainly associated with the observation scale. However, the emergence of new research techniques and development of traditional techniques, coupled with increasingly accurate assessments, enables existing research gaps to be filled. For example, this applies to measurements of the hardness, Young’s modulus, and roughness, which can be measured in areas of <1 μm² via atomic force microscopy (AFM) and nanoindentation [30]. This allows for the creation of property maps and the assessment of the anisotropy of these properties at the level of the basic structural units of enamel, e.g., prisms [31]. Literature results of the study of enamel properties are presented in Table 2.

In Table 2, significant differences in the values of individual parameters are observed. This is a result

Table 2. Selected properties of human tooth enamel (average values or range of values)

Parameter	Method of measurement	Value	Source
1	2	3	4
Hardness	Nanoindentation (Berkovich indenter)	4.6 GPa (near surface) 3.4 GPa (near dentine)	[27]
	Nanoindentation (Berkovich indenter)	3.66 GPa (mean)	[32]
	Nanoindentation	4.45–4.74 GPa	[33]
	Nanoindentation (Berkovich indenter)	3.9 GPa (prisms) 1.4 GPa (interprisms)	[34]
	Nanoindentation (Berkovich indenter)	4.75–4.81 GPa	[35]
	Vickers microhardness	270–390 HVN (cross section along tooth axis) 327–397 HVN (cross section perpendicular to tooth axis)	[36]
	Vickers microhardness	3.0 GPa	[37]
	Nanoindentation	3.81 ± 0.73 GPa (at load of 50 mN) 4.11 ± 0.94 GPa (at load of 150 mN)	[38]
	Knoop microhardness	258–296 HKN	[39]
	Nanoindentation (Berkovich indenter)	4.78 GPa (along tooth axis) 4.53 GPa (perpendicular to tooth axis)	[40]
	Vickers microhardness	337.2–355.3 HVN	[41]
	Vickers microhardness	3.62 GPa (cross section along tooth axis)	[42]
	Vickers microhardness	3.37 GPa (cross section perpendicular to tooth axis)	[43]

Table 2 continued

1	2	3	4	
Young modulus	Nanoindentation (Berkovich indenter)	91.1 GPa (near surface) 66.2 GPa (near dentine)	[27]	
	Nanoindentation (Berkovich indenter)	75.57 GPa (mean)	[32]	
	Nanoindentation (Berkovich indenter)	77.1 GPa (prisms) 41.2 GPa (interprisms)	[34]	
	Resonant ultrasound spectroscopy	60.7–80.5 GPa	[44]	
	Compression test	131 GPa	[45]	
	Compression test	84.1 GPa	[46]	
	Compression test	5.64 GPa	[47]	
	Acoustic microscope	62.7 GPa	[48]	
	FEM modelling	93–113 GPa (parallel to prism axis) 19–91 GPa (perpendicular to prism axis)	[49]	
	Nanoindentation (Berkovich indenter)	99.6–105.2 GPa	[35]	
	Piezoelectric activation	95 GPa	[50]	
	Nanoindentation (Berkovich indenter)	95.6 GPa (along tooth axis) 98.3 GPa (perpendicular to tooth axis)	[40]	
	Nanoindentation (indenter – cube corner)	60–70 GPa	[51]	
	Vickers indentation	94 GPa (cross section parallel to tooth axis) 80 GPa (cross section perpendicular to tooth axis)	[43]	
Stiffness	Tensile	48.7×10^4 N/mm ² (mean)	[52]	
	Compression	16.6×10^4 N/mm ² (mean)		
	Compression	17.0×10^4 N/mm ² (mean)	[53]	
Ultimate tensile strength	Static tensile microtest	42.2 MPa (parallel to prism axis)	[54]	
	Spherical indentation	119 MPa	[55]	
	Microtensile test	47.5 MPa	[56]	
Ultimate compressive strength		267 MPa 297 MPa 348 MPa 288–400 MPa 275 MPa	[57] [46] [58] [59] [60]	
	Diametral compression	39.9 MPa	[61]	
	Toughness		0.94 MPa m ^{1/2} 1.34–1.77 MPa m ^{1/2} 0.35 (old teeth) MPa m ^{1/2} 1.23 (young teeth) MPa m ^{1/2} (both for crack growth transverse to the enamel prisms)	[55] [62] [63]
			0.9 MPa m ^{1/2} (along prism axis)	[37]
		Vickers indentation	1.3 MPa m ^{1/2} (transverse to prism axis)	
		Vickers indentation	0.77 MPa m ^{1/2} (transverse to tooth axis)	[43]
		1.32 MPa m ^{1/2} (along prism axis)		
Yield strength	Compression	75.8 MPa	[57]	
	Compression	353 MPa	[46]	
	Compression	1940 MPa	[53]	
	Compression	331 MPa	[64]	
	Spherical indentation	330 MPa	[65]	
Share strength		39 MPa 64–93 MPa 38.4–45.9 MPa (normal to prisms) 146.7 MPa (parallel to prisms)	[66] [67] [68]	
	Roughness	3D profilometry	Sa 2.03 µm	[69]
		3D profilometry	Sk of contact area 0.92 (molar) 1.48 (premolar) 0.50 (canine)	[70]
		AFM	Ra 139 nm	[71]
Perfilometry		Ra 0.089 µm	[72]	
Contact profilometry		Ra 0.647–0.794 µm	[73]	
3D profilometry	Sa 1.06 µm	[74]		
Density		2.9 g/cm ³ 2.83–3.00 g/mL	[60] [75]	

Table 2 continued

1	2	3	4
Surface free energy		77–87 mJ/m ² 54.9–56.3 mN/m. 78.3 mN/m	[76] [77] [78]
Thermal conductivity		0.88 W/mK 0.81 W/mK 0.7–0.8 W/mK	[79] [80] [81]
Thermal expansion coefficient		11.4 ppm/°C 16.96 × 10 ⁻⁶ /°C	[79] [82]
Electrical resistance	At temperature of 25 °C At temperature of 350 °C	10 ¹⁵ Ω 10 ⁵ Ω	[83]

of the substantial heterogeneity of the enamel in a single tooth, which is visible at different levels of observation (from the macroscale to the nanoscale) [84], as well as inter-individual and age-related differences [85], [86]. Additionally, the obtained test results significantly depend on the technique or the test parameters used. For example, consider the results of microhardness tests at different indenter load values performed by Zhang et al. [87]. The average microhardness of the tested samples was 453 HVN at a load of 50 g, whereas for a load of 2000 g, the average value was 328 HVN (lateral tooth surface). This discrepancy indicates the difficulty of researching tooth enamel. Thus, despite some insurmountable difficulties, it is imperative to standardise the testing of enamel. This is important for tribological studies, which are characterised by a high degree of randomness. The variability of the features of the study object increases this randomness, causing difficulties in drawing conclusions.

The dental organ should be treated as a system operating in the presence of a lubricant. According to the Czichos methodology, saliva is located in the material plane. One of the most important functions of natural saliva is to ensure the lubrication of contacting teeth, as well as the contact of the teeth with oral soft tissues. The good lubricating properties of saliva reduce the friction between teeth, between teeth and food, and between teeth and the tongue or mucosa [88]–[90]. Consequently, soft tissues are protected from damage, and excessive wear of the teeth is prevented. Appropriate lubrication inside the mouth is important for functions such as chewing and swallowing and also affects speech quality. Deterioration of the quality of saliva due to diseases or a significant reduction in its secretion (as in the case of Sjögren syndrome) increases the intensity of tooth wear [91]. The multifunctionality of saliva depends on its composition, which changes according to the food consumed, time of day, age, medications taken, and mental state [92]. Saliva has a complex structure, and there are concepts in the

literature according to which saliva should be treated as a tissue rather than a fluid [93]. In Table 3, the functions of saliva and the ingredients responsible for these functions are presented.

Table 3. Functions and corresponding components of human saliva (source: [94])

Function	Components
Antibacterial function	Amylase, cystatins, mucins, histatins, peroxidase
Buffering	Carbonic anhydrase, histatins
Digestion	Amylase, lipase, mucins
Mineralisation	Cystatins, histatins, proline-rich proteins, statherin
Lubrication	Mucins, statherin
Adherence to enamel	Amylase, cystatins, mucins, proline-rich proteins, statherin
Antifungal activity	Histatins
Antivirus activity	Cystatins, mucins

6. Dental organ: inputs and outputs

The diverse food that undergoes initial formation in the oral cavity is the object of “recognition” by the neuromotor system associated with the function of the dental organ [95]. Ensuring the effectiveness of the chewing process requires that the system input comprises appropriate kinematic parameters and appropriate load values. The input parameters (forcing) are characterised by the specific dynamics during a single chewing cycle. It is widely accepted that the load during a single cycle varies according to the positive half of the sine wave [96]–[99]. However, Kohyama’s studies on the kinetics of chewing revealed an asymmetric load curve, and the time taken to reach the maximum chewing force was 59–67% of the entire

Table 4. Selected dental-organ work parameters

Parameter	Comments	Quantity	Source
Biting and chewing forces	Incisors	100 N	[102]
	Molars	500 N	
	Parafunctions (e.g., bruxism)	500–800 N	
	Incisors	33–37 N	[103]
	Molars	100–127 N	
	Whole tooth arch	70–370 N	[104]
	Whole tooth arch	25–290 N	[105]
	Maximum value at teeth clenching	1181 N	[106]
Contact pressure		1 MPa	[100]
		33.9 ± 5.8 MPa	[107]
		200 MPa	[108]
	Computer simulation	86 MPa	[109]
	Computer simulation	41.2 MPa	[106]
Occlusion duration		0.10–0.12 s	[110]
		0.25–0.30 s	[111]
Duration of single chewing cycle		0.66–0.73 s	[110]
	Male–female	0.75–0.79 s	[112]
		0.84–0.97 s	[113]
Daily number of cycles		1500–15000	[108]
Speed of mandible during chewing	Lateral movement	25 mm/s	[110]
	Lateral movement	50 mm/s	[112]
	Chewing of gum	64 mm/s	[114]
	Chewing of carrots	75 mm/s	
	Lateral movement during gum chewing (male–female)	26–28 mm/s	[113]
Food temperature		–10 to 50 °C	[108]
		0 to 70 °C	[115]
Environment pH		1–9	[108]

cycle time [100], [101]. The values of the dental organ work parameters are presented in Table 4.

The values of the forces loading the teeth during biting and chewing change within wide ranges and depend on the type of food and the position of the tooth in the dental arch [106]. Research also indicates high interindividual variability [104].

From a tribological point of view, knowledge of the contact pressure is more important than knowledge of the normal forces [107]. However, measuring the pressure during mastication poses significant methodological problems. Hence, there are considerable discrepancies in the literature that cannot be explained by the variability of the chewing conditions (various types of food) alone.

The proper formation of food during chewing requires specific mandible kinematics. It involves spatial movement whose parameters depend mainly on the type of food consumed. A general diagram of mandible movements, which was developed on the basis of available literature data [20], is presented in Fig. 9.

An important input parameter for any tribological system is the temperature of the surrounding environment. From a tribological point of view, the temperature of the autonomous environment can be considered as a constant. However, significant changes, which are

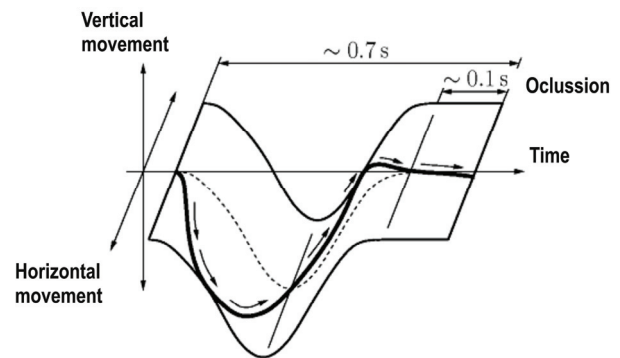


Fig. 9. Trajectory of the mandible movements during a single chewing cycle (reproduced with permission from ref. [20])

associated with the type of food consumed (particularly for liquids), occur in the external environment. The range of temperatures is wide, and the level of acceptance of the oral tissue environment (measured by time of stimulus tolerance) decreases at extreme temperature values. These are temperatures (Table 4) that do not cause degradation of the enamel substance or changes in its properties because the evaporation of water in biological hydroxyapatite is observed only after the temperature exceeds 120 °C and permanent loss of organic

matter occurs above 200 °C [16]. However, temperature changes (particularly increases) can significantly change the rheological properties of saliva and affect the adsorption of its components responsible for the formation of boundary layers. This can lead to significant changes in the lubrication conditions of tooth surfaces (enamel) and, consequently, the lubrication regime. The foregoing problem has not yet been experimentally studied.

Among the parameters that may affect the tribological processes involving the dental organ, the “environmental chemistry” probably exhibits the greatest dynamics of changes. It is naturally associated with the intake of a variety of foods but can also be a consequence of certain diseases (e.g., gastric diseases, frequent vomiting associated with bulimia or alcohol abuse). Particularly important here is the high acidity of the environment, which adversely affects the durability of the enamel, because, apart from strong chemical effects, it can also intensify tribological processes.

The system output can be treated as a **functional output** [116], which characterises the basic function of the system (in our case, the formation of the material). The characteristics of the output thus defined can be represented by the parameters (properties) of the processed material [117], [118]. However, when treating a dental organ as a tribological system, it is more pragmatic to employ commonly used tribological characteristics such as the friction coefficient and/or wear intensity as well.

7. Some methodological problems of dental biotribology

Tribological examinations of the dental organ present numerous issues related to the assessment of the behaviour of natural materials (hard tooth tissues) or

artificial materials (materials used in conservative dentistry, prosthodontics, orthodontics) during friction. The crucial question is how to conduct such research for obtaining reliable results corresponding to actual clinical situations. The question is fully justified, because the wide variety of research techniques and methods observed in practice often leads to conflicting research results regarding the same issues (objects, processes). This problem is illustrated by the published work of Heintze et al. [119], who compared the tribological wear resistance of 10 dental restorative materials using seven widely employed experimental devices.

In Table 5, the ranking of the tested composite materials based on the results from the cited work is presented (the material with the best tribological features is ranked number 1, and the material with the worst features is ranked number 10). The method used to test the resistance of dental materials to tribological wear significantly affected the test results. This is clearly revealed by a comparison of the Chromasit wear-resistance test results obtained using the MUNICH method (2nd in the material ranking) and other methods (10th in the ranking). Therefore, a reliable method for objectively assessing the tribological properties of materials used in dentistry and predicting the behaviour of these materials in clinical conditions must be developed.

The obvious conclusion that can be drawn on the basis of the foregoing considerations is that **the material’s resistance to tribological wear is not a universal property but a parameter characterising a specific tribological process**. Thus, not the **material’s resistance** but the **material’s resistance to tribological wear under certain conditions** can be discussed. Therefore, we cannot apply quantitative assessment with a single number here, as is possible for properties such as the thermal conductivity and electrical resistance. This also explains the large discrepancy in the results in the work cited above. The use of research methods (devices) that differ significantly in the level and nature of the

Table 5. Ranking of dental materials; the order is determined on the basis of a tribological wear resistance assessment (according to various research methods) [119]

Material/Method	IV VOL	IV VERT	ZURICH	OHSU-ABR	OHSU-ATT	MUNICH	ACTA
Empress	4	3	1	2	3	8	1
BelleGlass	3	4	2	5	4	6	4
SureFill	5	5	5	4	5	5	5
Estenia	8	8	3	3	2	10	2
Targis 130	7	7	4	8	9	3	6
Amalcap	2	2	7	1	1	9	3
Targis 95	6	6	6	7	7	4	7
Heliomolar RO	1	1	9	6	6	1	9
Tetric Ceram	9	9	8	9	10	7	8
Chromasit	10	10	10	10	9	2	10

load, kinematics, and environmental parameters leads to a variety of wear mechanisms and consequently to a differentiation of the intensity of wear process.

Numerous methods, sometimes considerably different from each other, are used to study the tribological characteristics of hard tooth tissues and dental materials. The wide variety of methods results from the high complexity of tribological processes and the lack of a universally accepted method, allowing for comprehensive assessments. The methods can be divided into two main groups: *in vitro* and *in vivo*.

The most clinically valuable results are obtained when the test is conducted in the oral environment (*in vivo*). Unfortunately, in addition to the undoubted advantages, such studies have disadvantages, including high costs, time consumption, ethical problems, and the lack of control (measurement) of parameters affecting the results. *In vivo* tests also have significant methodological difficulties in evaluating the wear, although significant progress has been made. Nonetheless, such research provides valuable **statistical** data and is the important way to verify the performance of dental materials. The foregoing considerations give rise to the wide popularity of *in vitro* methods, which significantly reduce the testing time and allow for precise control of the parameters affecting the tribological behaviour of the tested materials. An important disadvantage of these studies is that the conditions under which they are performed often differ significantly from the conditions of the oral cavity, and the results can be used only to a limited extent to predict the behaviour of dental materials in clinical conditions. Researchers have attempted to overcome these difficulties by constructing devices with parameters as close as possible to those of the oral cavity (particularly during chewing). An example of such a device is the “artificial oral environment”, which was developed by DeLong and Douglas [120]. This solution involves the exact replication of the kinematics associated with chewing and the associated load. Some “most likely” patterns occurring during chewing, i.e., the trajectory of tooth movement and load values, are adopted. However, the actual operating conditions of the stomatognathic system exhibit a random nature, and the load values change within very wide limits (Table 5). Additionally, significant inter-individual variation occurs in the chewing pattern; according to Ahlgren [121], seven basic patterns can be distinguished. Thus, devices reproducing the “most likely” working conditions of the dental organ may implement only one of many possible scenarios. Therefore, correct (comprehensive) reproduction of clinical conditions in *in vitro* tests appears to be impossible.

Nevertheless, despite their **quantitative** nature, tests performed under laboratory conditions provide valuable qualitative information that makes proper interpretation of results obtained *in vivo* possible.

One of the basic parameters evaluated in tribological tests is the wear (wear intensity, wear rate) of materials or hard tissues. Accurate determination of the wear value is sometimes difficult and requires consideration of numerous factors.

In *in vivo* research, one of the basic methods used to quantitatively assess tooth wear is the replica method [122], [123]. The main difficulty in using this method is the determination of constant (over time) reference points, i.e., base points, relative to which the locations of surface points are determined. This difficulty is not resolved by the introduction of laser scanners that allow for accurate restoration of the tooth surface *in situ*. Researchers have recently recommended avoiding the replica method owing to its low accuracy, particularly for the assessment of short-term wear. The use of intraoral digital profilometers and matching software is promising [123].

The main problem in assessing wear under laboratory conditions is selecting the assessment method, i.e., deciding whether to assess linear, volumetric, or mass wear. However, measurements of the wear of dental materials and hard dental tissues are often characterised by a large dispersion, which makes it difficult to draw conclusions. The poor repeatability of tribological research results has long been a problem in tribology [124] and can be attributed to the high sensitivity of the tribological system to external disturbances [125]. However, because we are dealing (particularly with regard to hard tooth tissues) with a nonhomogeneous material, as well as inter-individual differences, additional measurement uncertainty arises. The problem is illustrated in Fig. 10,

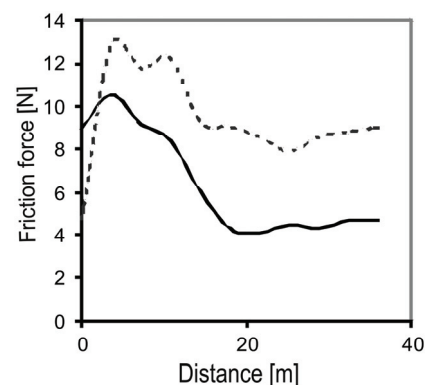


Fig. 10. Friction force recorded during testing of two enamel samples from different people (unit pressure value was 20.3 MPa in both cases; wear was 0.041 mm³ for the course marked with a solid line and 0.065 mm³ for the course marked with a dashed line) (reproduced with permission from ref. [126])

which shows the course of the friction force in a test of enamel from two people. Despite the similar values of the unit pressure and microhardness for the two samples (system input), significant differences were observed in the courses of the friction resistance (system output) [126]. Thus, significantly different wear values were obtained.

The methods of assessing tribological parameters of the system that dominate in engineering practice are derived from the Coulombic concept of friction and are essentially static, thus, they do not take changes resulting from the dynamics of the tribological system into account. Some proposed energy approaches make considering of these dynamics possible, and the results of applying new concepts are very promising [125], [127]–[130]. The practical advantage of this approach is expressed in the fact that if the test experimental system (tribometer, simulator) is equipped with a friction force sensor, the most conveniently its measured wear relates to the friction work inserted during the test. Calculating the specific wear energy allows various test conditions to be “normalised” and thus allows for more reliable assessments of the tribological properties. Experimental verifications of the method for hard tooth tissues and dental materials were reported [126], [128], [131].

The aforementioned mainly practical aspects of dental-organ research clearly indicate the need for methodical ordering. The peculiarity of the dental organ, as a biotribological system, resulting from the presence of an additional (autonomous) environment and specific phenomena (processes), such as homeostasis, causes the appearance of numerous new relationships. This is clearly observed when comparing the relationship patterns of a simple sliding bearing (tribological system) and the dental organ (biotribological system) (Figs. 11 and 12). Therefore, the dental organ exhibits not only specific features of the biotribological system but also high complexity, making it more difficult to analyse.

If the relationships in the bearings are expressed by the matrix (E – environment):

$$R_{TS} = \begin{matrix} & \text{Output} \\ \text{Input} & \begin{bmatrix} S_{01} & S_{02} & S_{03} & 0 \\ S_{11} & S_{21} & S_{31} & S_{10} \\ S_{12} & S_{22} & S_{32} & S_{20} \\ S_{13} & S_{23} & S_{33} & S_{30} \end{bmatrix} \end{matrix} \quad (2)$$

and the relationships in the dental organ are expressed by the matrix (EE – external environment, AE – autonomous environment):

$$R_{DO} = \begin{matrix} & \text{Output} \\ \text{Input} & \begin{bmatrix} S_{01} & S_{02} & S_{03} & S_{04} & S_{05} & EE \\ S_{11} & S_{12} & S_{13} & S_{14} & S_{15} & S_{10} \\ S_{21} & S_{22} & S_{23} & S_{24} & S_{25} & S_{20} \\ S_{31} & S_{33} & S_{33} & S_{34} & S_{35} & S_{30} \\ S_{41} & S_{42} & S_{43} & S_{44} & S_{45} & S_{40} \\ \text{Input} & \begin{bmatrix} S_{51} & S_{52} & S_{53} & S_{54} & AE & S_{50} \end{bmatrix} \end{bmatrix} \end{matrix} \quad (3)$$

the higher complexity of the dental organ (biotribological system) compared with the engineering tribological system becomes evident.

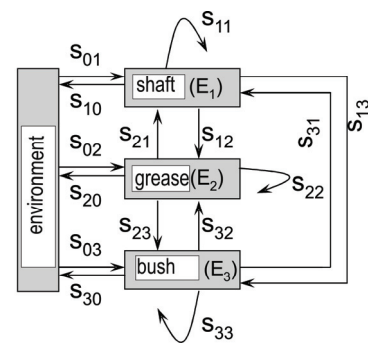


Fig. 11. Diagram of relationships in a simple sliding bearing

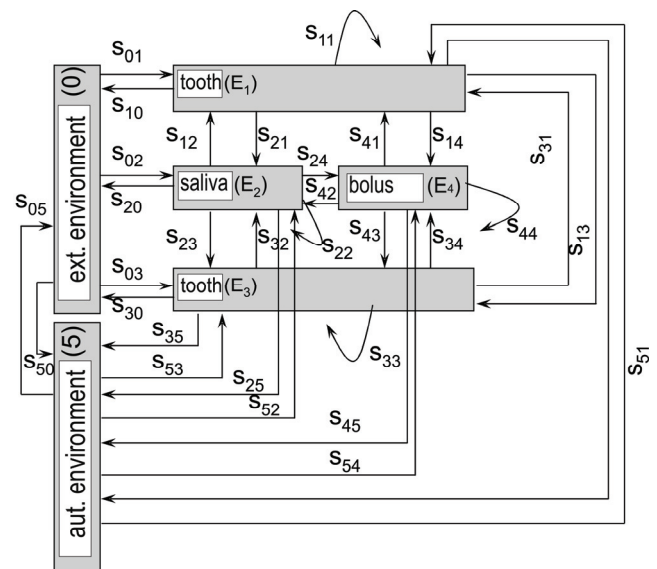


Fig. 12. Diagram of relationships in the dental organ (for clarity, the relationships S_{40} and S_{04} are not included)

The dental organ in its entirety and some of its components (particularly enamel) exhibit locally conditioned structural diversity, which is essential for tribological behaviour. This significantly affects the properties of its individual elements, depending on the location (method) of their assessment. Neglecting this may result in methodological errors and ambiguous test results. An example is the difference in the assessment

of the impact of the prism orientation on the mechanical properties of enamel. According to Spears [132], the enamel exhibits significantly higher stiffness in the direction of the prism axis than in the direction perpendicular to this axis. These results – obtained using finite-element method (FEM) modelling – were contradicted by Cuy et al. [27], who reported only a weak correlation between the Young’s modulus and the orientation and found that the measurement location on the enamel cross section and the chemical composition significantly affected the mechanical properties.

The foregoing indicates the need to introduce methodological principles that may allow for consistent results of dental organ tests to be obtained. To this end, the concepts of the **level of observation** and isolation from the system of the corresponding **object of research** are introduced. The following levels are considered:

- geometry
- structure
- architecture.

The proposed classification does not constitute the decomposition of the system and is not a hierarchical representation of it but only covers the differentiated orientation of insights constituting the essence of scientific observation. It appears that examples will provide a good illustration of the presented approach. For example, observations from the level of geometry correspond to the observations we make when examining the impact of a bite of food on the tooth surface. This was investigated by Spears and Crompton [133], who examined the relationship between diet and dentition for mammals. Assuming that the structure implies the existence of specific relationships in the system, the study of the effect of the Ca/P ratio in the enamel on its resistance to tribological wear corresponds to observations

from the level of structure. The study of the impact of ordered arrangement of prisms, e.g., according to the Retzius or Hunter–Schreger lines, on the system’s tribological characteristics corresponds to observations from the architecture level. Owing to the conceptual nature of the proposed approach, there are no clear (physical) boundaries between the levels, and some relationships can be distinguished between them. A graphical representation of the observation levels for tribological examinations of the dental organ is shown in Fig. 13.

8. Conclusions

Recently, biomedical engineering has seen intensive development in areas related to biotribology. Considerable progress has been achieved in elucidating the processes associated with the friction phenomenon in living organisms, as well as in the application of new devices, materials, and equipment, whose functions in the friction pairs of the body have been significantly improved.

Among the areas of medicine, dentistry is also of interest to biotribologists, as it involves processes and phenomena related to the stomatognathic system and its main part: the dental organ. This organ functions under complex mechano-physico-chemical conditions and its analysis can yield results that not only are useful for improving the durability of teeth but also add to the overall body of knowledge of tribology.

Owing to significant progress, mainly in the field of research technology, an important step in the development of dental biotribology was recently achieved. It appears that further progress in this area may lead to the application of new methodological solutions, i.e., more comprehensive use of the well-known achievements of the general systems theory in dental biotribology. This approach allows for more comprehensive tribological analysis of the dental organ. According to the results of the present study, the following important conclusions are drawn:

- 1) similarly to other biotribological systems, the dental organ has an “autonomic” environment, which significantly increases the number of tribological relationships and complicates the analysis;
- 2) knowledge of the attributes of the dental organ that were discussed in this paper, i.e., the structure (elements, properties, and relationships), functions, and system inputs and outputs, can be useful in studying detailed aspects of the function of the dental organ;

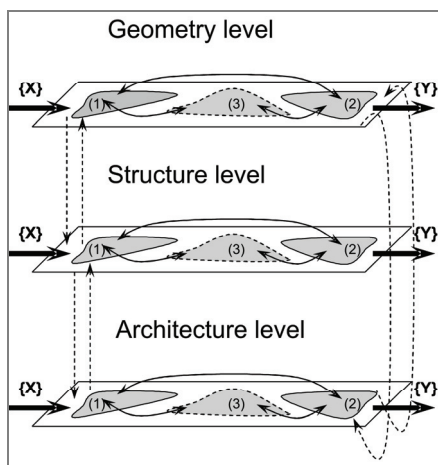


Fig. 13. Observation levels in the study of the tribological properties of the dental organ (X and Y represent the system inputs and outputs, respectively; 1, 2, and 3 indicate the system elements)

- 3) the specific features of the analysed system and (above all) the unique structure necessitate the use of appropriate method for testing the properties. To this end, it is beneficial to extract observation objects (material objects or processes) from the system and assign proper observation levels to them. The following levels of observation are proposed: geometry, structure, and architecture.

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Ethics approval and consent to participate

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Consent for publication

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Competing interests

The author declares that there was no conflict of interest.

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