ORIGINAL ARTICLE

CONTENTS

Determination of tongue pressure force: Experimental research

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ABSTRACT

Aim: To identify the zones of maximum contact force (F, N) of the tongue at 100% and 125% tongue volume on areas of the oral cavity in an experimental study, and to conduct a comparative analysis of the contact force indicators.

Materials and Methods: 3D prototypes of the patient's upper and lower jaws were created. Measurements were carried out using a FlexiForce film force sensor and an Arduino Nano microcontroller module. This allowed recording of the contact force applied by the tongue.

Results: The maximum values of contact force were recorded in the following areas: the marginal gingiva on the lingual surface of the lower central incisors, the marginal gingiva on the palatal surface of the upper central incisors, the middle third on the lingual surface of the lower central incisors, and the middle third on the palatal surface of the upper central incisors. An increase in values was noted in all studied zones when the tongue volume increased to 125%.

Conclusions: A comparative analysis of tongue contact force indicators obtained during the experimental study demonstrated an increase in values when the tongue volume was enlarged to 125% in the areas of the oral cavity of the upper and lower jaws, compared with the actual tongue volume.

KEY WORDS: maximum stress concentration, dentognathic anomalies and deformations

Wiad Lek. 2026;79(6):1273-1279. doi: 10.36740/WLek/222569 DOI

INTRODUCTION

The tongue has an important role in the functioning of the dentognathic apparatus [1, 2]. Excessive pressure of the tongue on surrounding structures – especially when its size increases, its habitual static position changes, or its function is impaired – leads to alterations in the anatomical and topographical relationships with adjacent tissues and is considered a primary aetiological factor in the development of pathological occlusions [2, 3].

Permanent tongue enlargement (macroglossia) can be attributed to muscular hypertrophy or hyperplasia (primary macroglossia) or to an underlying condition (secondary macroglossia). Secondary macroglossia may be associated with congenital or acquired factors (Down syndrome, Beckwith–Wiedemann syndrome, neurofibromatosis type I, idiopathic muscular hypertrophy, etc.), metabolic/endocrine disorders (hypothyroidism, myxoedema, acromegaly, amyloidosis), inflammatory/infectious, systemic, traumatic, and neoplastic factors (congenital lymphangiomas or vascular malformations). The distorted interrelations between a hypertrophied tongue and surrounding bony structures (maxilla, mandible, alveolar process, and dental arches) can significantly influence their growth and development, especially in childhood and early adolescence. At the same time, the exact mechanisms of tongue-associated maxillofacial and occlusal abnormalities are not yet well understood. The multifactorial nature of orthognathic pathology and limited data concerning the biomechanical influences of the enlarged tongue (contact pressure, functional force, and their influence on stress and strain distribution within the growing bone) cause significant uncertainty and controversy in treatment and prevention strategies. Due to the specific structure of the tongue, the diagnosis of macroglossia and the extent of its enlargement is quite complex [2, 4–6], with no clear evidence of a correlation between tongue dimensions and the severity of the resulting orthodontic pathology. In this context, experimental studies conducted through mechanical and mathematical modelling, modern computer technologies, and the construction of three-dimensional simulation models of the biomechanical system "tongue–dentognathic apparatus" are of particular importance [7–9].

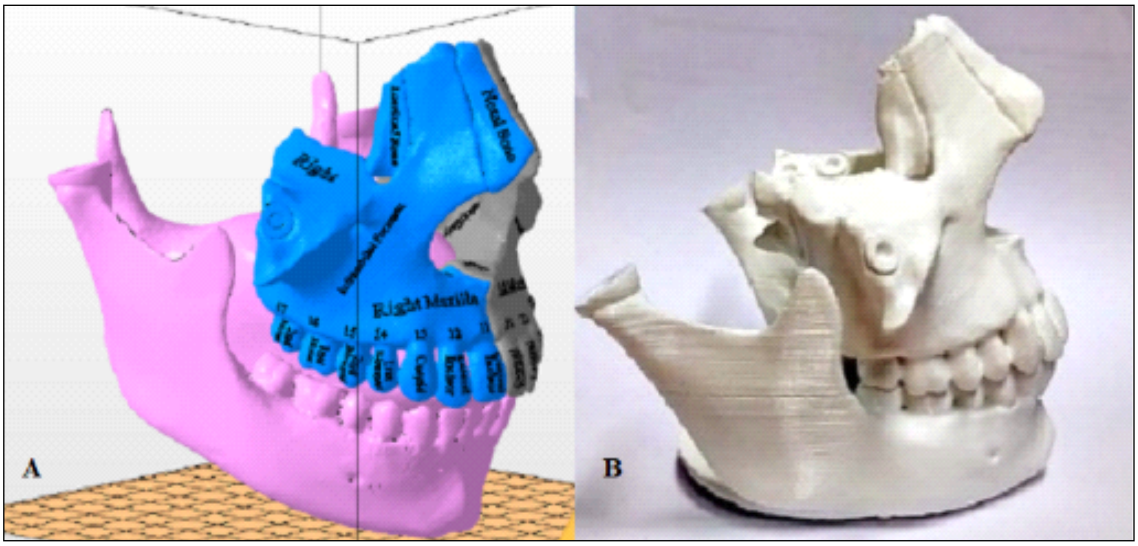

Fig. 1. 3D prototypes of the patient's jaws based on CBCT scans of the skull (A), 3D prototypes of the jaws printed on a 3D printer (B)
Picture taken by the authors

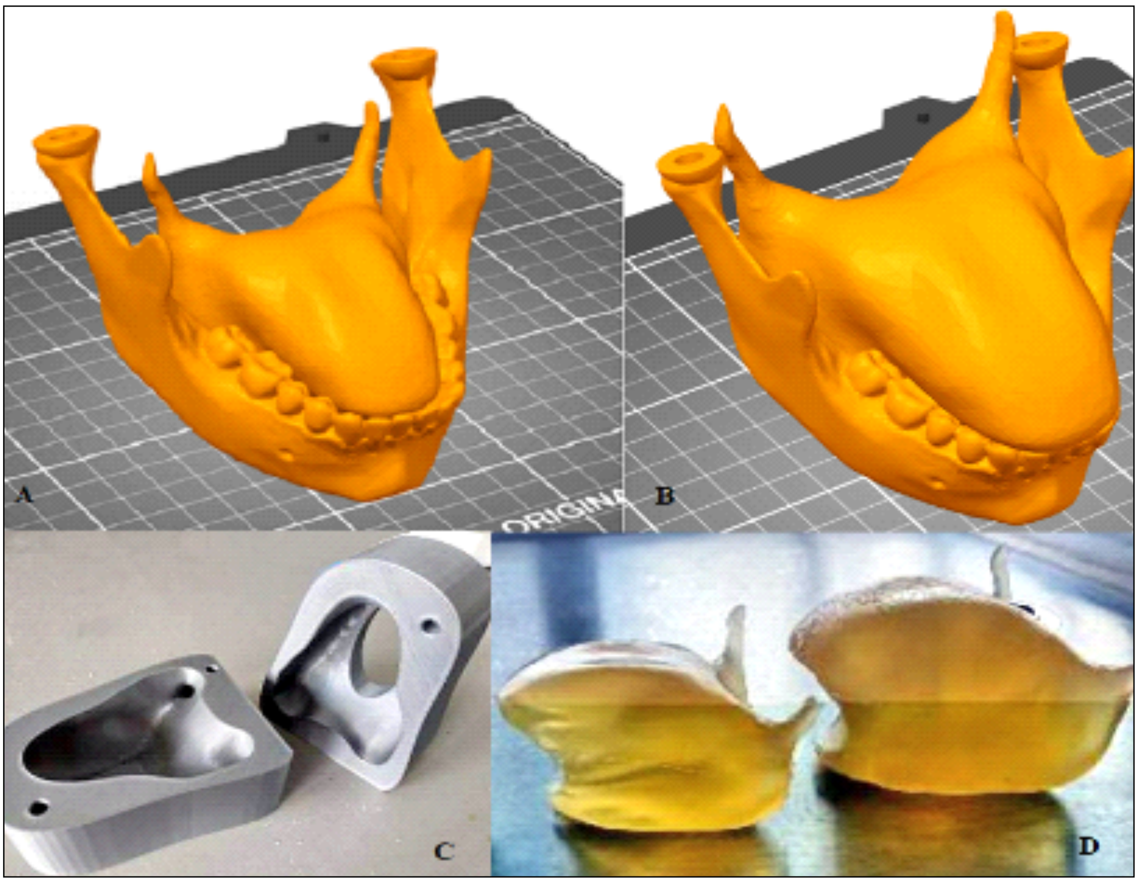

Fig. 2. 3D-printed tongue prototypes with 100% (A) and 125% (B) volumes in the mandibular space, a tongue mold made of PLA (Prusa PLA, Prusa Research a.s., Prag, Czech Republic) (C), and ballistic gel tongue models with 100% and 125% volumes (D)
Picture taken by the authors

AIM

To identify the zones of maximum contact force (F, N) of the tongue at 100% and 125% tongue volume in the areas of the oral cavity of the upper and lower jaws in an experimental study, and to conduct a comparative analysis of the contact force indicators.

MATERIALS AND METHODS

Cone-beam computed tomography (CBCT) and magnetic resonance imaging (MRI) were used in this study for patient M., aged 12, who sought care at Children's Clinical Hospital No. 7, Department of Surgical Dentistry and Maxillofacial Surgery of Paediatric Age, Bogomolets

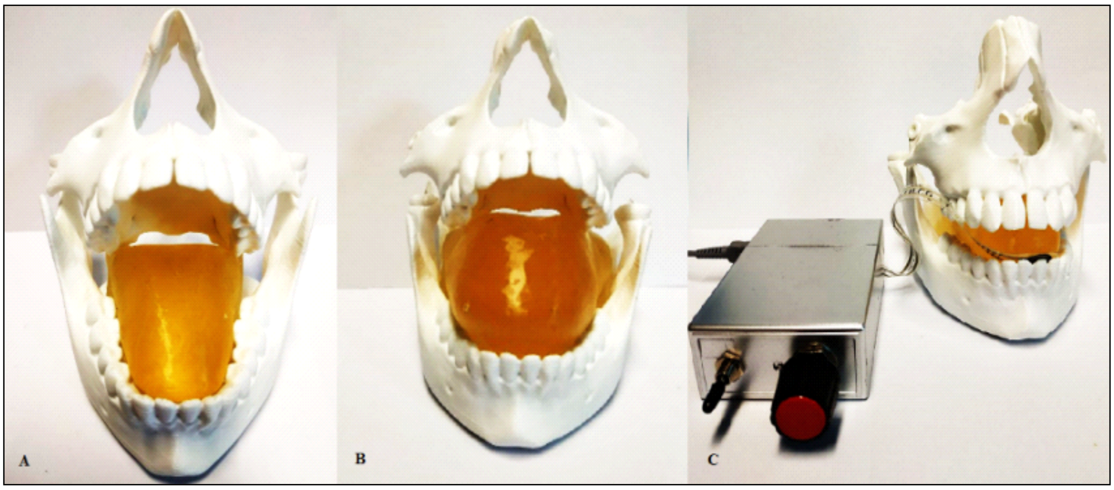

Fig. 3. Ballistic gel tongue models with volumes of 100% (A) and 125% (B) in the mandibular space, and an electronic device based on an Arduino Nano microcontroller module with a FlexiForce thin-film force sensor (C)
Picture taken by the authors

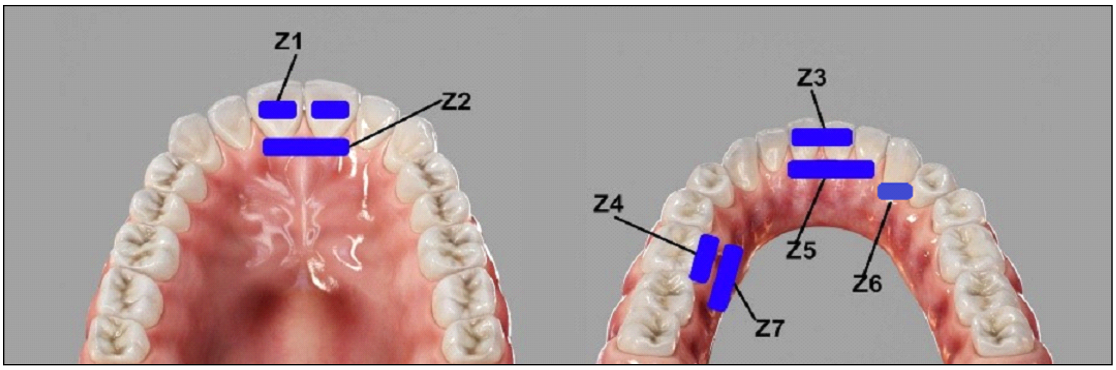

Fig. 4. Zones of maximum contact force (F, N) of the tongue fixation on areas of the oral cavity in the upper and lower jaws
Picture taken by the authors

National Medical University, for general medical indications. The patient was found to have a physiological (orthognathic) bite, with no functional disorders of the maxillofacial region.

The first step was the creation of 3D prototypes of the patient's upper and lower jaws based on CBCT scans of the skull. The base model was derived from a geometry obtained from Thingiverse, an open online repository of user-generated 3D models, provided under a Creative Commons licence for non-commercial use [10]. Since the model is modifiable, Boolean operations were applied in Siemens NX software (Ver. 2015, 2202) to connect the components of the upper jaw and to smooth the palatal fissure that had formed (Fig. 1A). The jaw prototypes were printed using an FDM 3D printer (Prusa Mk3S+, Prusa Research a.s., Prague, Czech Republic) and PETG filament FIL-A-GEHR PETG® (Gehr GmbH, Mannheim, Germany) (Fig. 1B).

The MRI scans of the tongue were segmented using 3D-Slicer (Ver. 4.13.0), and an STL file of its surface was created. Then, a two-component mold of a normal anatomical tongue model was designed using Siemens NX software (Ver.2015, 2202). The next step, also performed in Siemens NX, involved scaling the STL model of the tongue to 125% volume (Fig. 2A, B). Molds for 3D printing were fabricated from polylactic acid (PLA, Prusa PLA) using a Prusa MK3S+ 3D printer (Prusa Research, Co) (Fig. 2C).

Ballistic gelatin was selected as the tongue prototype material for the study [11, 12]. In terms of mechanical properties, this material closely approximates the actual density of the human tongue. The composition of ballistic gelatin is tailored to simulate the physical properties of living human tissues (viscosity, density, resistance) in experiments studying the impact of firearms, mines, or explosive devices. Human muscle tissue consists of approximately 75% water; ballistic gelatin enables the mechanical properties to be modelled with a high degree of similarity by binding the liquid phase into a form suitable for experimentation.

In addition to water and isopropanol (99,9%), glycerin and porcine gelatin were used to prepare the artificial tissue. Before adding the other ingredients, the porcine gelatin powder was mixed with water and left to swell

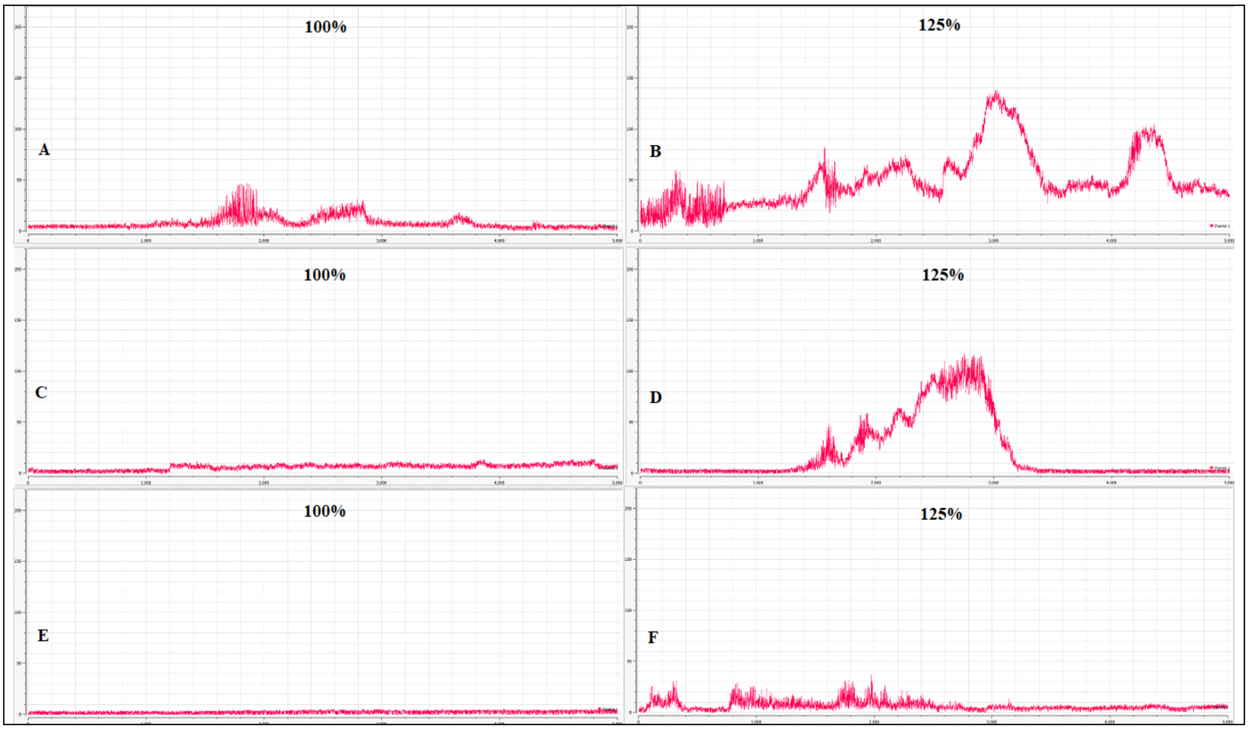

Fig. 5. Time-based registration of contact force (F, N) of the tongue using SerialPlot software graphs at tongue volumes of 100% and 125% in the zones of the marginal gingival on the lingual surface of the lower central incisors (A, B), marginal gingival on the palatal surface of the upper central incisors (C, D), and marginal gingival on the lingual surface of the lower canines (E, F)
Picture taken by the authors

for 10 minutes. The mixture was then heated in a water bath at 60 °C until fully dissolved, to obtain a clear fluid. One litre of ballistic gel was prepared using the following proportions: 500 ml of distilled water, 250 ml of isopropanol (99,9%), 250 ml of glycerin (>87%), and 162 g of porcine gelatin. Before slowly pouring the mixture into the moulds, both parts of the mould were joined together (Fig. 2D). Following the moulding process, the mould was placed in a temperature-controlled cooling chamber (4 °C) for 12 h to ensure uniform thermal dissipation. After reaching ambient temperature, the final step involved demoulding the specimen.

3D models of the tongue at 100% and 125% volume were obtained and subsequently placed, one at a time, within the space of the lower jaw (Fig. 3A, B). To perform the measurements, a FlexiForce thin-film force sensor was used, with a surface area (S, mm^2) of 78,5 mm^2, which enabled the recording of tongue pressure force values. An electronic device based on an Arduino Nano microcontroller module was used for data acquisition (Fig. 3C). The contact force (F) of the tongue was determined in N from the sensor readings.

Analog-to-digital conversion of the force sensor signal was performed using SerialPlot software after appropriate configuration in Arduino IDE. Following calibration with a 1 kg (9.81 N) reference weight, the FlexiForce thin-film force sensor was placed in the area between the tongue and both the middle third and marginal gingival part on the palatal surface of the upper teeth, as well as the lingual surface of the lower teeth. The model was closed manually with applied force until occlusion was achieved.

The following zones were chosen for sensor placement: Z1 – the middle third on the palatal surface of the upper central incisors; Z2 – the marginal gingival part on the palatal surface of the upper central incisors; Z3 – the middle third on the lingual surface of the lower central incisors; Z4 – the middle third on the lingual surface of the lower first molars; Z5 – the marginal gingival part on the lingual surface of the lower central incisors; Z6 – the marginal gingival part on the lingual surface of the lower canines; Z7 – the marginal gingival part on the lingual surface of the lower first molars (Fig. 4). These areas were chosen to distinguish the influence of macroglossia on different segments of the dental arches and alveolar bone, which are responsible for the development of certain types of occlusal anomalies.

ETHICS

In conducting this study, the authors complied with the ethical standards set forth in the World Medical Association's Declaration of Helsinki and current Ukrainian legislation, which regulate scientific research involving

Table 1. Contact force (F, N) of the tongue values in the corresponding zones of the upper and lower jaws in the experimental study

Zone	Model without restriction of distal tongue displacement		Model with restriction of distal tongue displacement	
	Contact force (F) of the tongue, N		Contact force (F) of the tongue, N	
	100%	125%	100%	125%
Z1	0	0	0.3	4.5
Z2	0	0	0.2	6.4
Z3	0.5	1.0	1.2	5.1
Z4	0.7	2.9	0.5	3.4
Z5	0.3	1.1	1.1	7.7
Z6	0.3	1.5	0.5	1.5
Z7	0.1	1.8	0.8	4.1

Source: compiled by the authors of this study

the use of medical records. The data used in the experiment were collected during additional examination after the patient was provided with clear, complete, and accessible information regarding the purpose, design, and methodology of the study, as well as the potential risks, benefits, and alternatives. The Commission on Bioethical Expertise and Ethics of Scientific Research of the Bogomolets National Medical University, Ministry of Health of Ukraine, reviewed the study materials and issued a recommendation for approval.

RESULTS

At 100% volume of the tongue, the values were insignificant. The maximum values of contact force (F, N) were recorded in the following areas: middle third on the lingual surface of the lower central incisors (Z3), marginal gingival part on the lingual surface of the lower central incisors (Z5), middle third on the lingual surface of the lower first molars (Z4) and marginal gingival part on the lingual surface of the lower canines, (Z6). An increase in contact force (F, N) of the tongue was observed in all studied zones of the upper and lower jaws when the tongue volume was increased to 125%. The maximum values of contact force (F, N) were recorded in the following areas: the marginal gingival on the lingual surface of the lower central incisors (Z5), the marginal gingival on the palatal surface of the upper central incisors (Z2), the middle third on the lingual surface of the lower central incisors (Z3), and the middle third on the palatal surface of the upper central incisors (Z1) (Fig. 5). Table 1 presents the contact force (F, N) applied by the tongue with and without restriction at the upper and lower jaw zones.

The highest values of contact force (F, N) at 100% and 125 % volume of the tongue were recorded in the following areas: the marginal gingival on the lingual surface of the lower central incisors (Z5) and the middle third on the lingual surface of the lower central incisors (Z3) (Table 1).

The quantity of established contact zones where the maximum pressure was determined at 100% and 125% volume of the tongue was higher on the lower jaw compared to the upper.

DISCUSSION

The majority of researchers agree that, despite its adaptive properties, the tongue has a significant role in the development of the dentognathic apparatus. The interaction between tongue force and the forces of the lips and cheeks is of particular interest when planning orthodontic treatment. Clear data on the distribution of maximum pressure gradients are lacking, as the tongue, situated within the oral cavity, can exert varying degrees of pressure on adjacent structures, thereby influencing the growth and development of the dentognathic apparatus [1, 2, 4–6].

Clinical studies on tongue pressure measurement are noteworthy. For example, Lee Y.S. and co-authors, using the Iowa Oral Performance Instrument, demonstrated possible differences in maxillofacial morphology depending on tongue muscle strength and lip pressure [13]. Tsujimoto K. and co-authors found that the greater the change in tongue mobility, the lower the pressure during protrusion and swallowing, and the worse the swallowing function in individuals with temporomandibular dysfunction [14]. Using a tongue pressure measurement device, Mizokami K. and co-authors established that occlusal contact area, maximum bite force, tongue pressure, and masticatory efficiency gradually increase with age, while lip pressure remains stable [15].

The most accurate data collection can be achieved by measuring tongue contact force in the anterior, posterior, and lateral areas of the oral cavity in both static position and during swallowing using flexible pressure sensors. For instance, Yu M. and Gao X. conducted an intraoral study to determine pressure in specific areas of the hard palate in individuals with various forms of dentognathic deformities. Their findings revealed a relationship between contact force, type of deformation, and dental arch morphology: the wider the dental arch, the lower the pressure exerted during swallowing in the anterior and lateral regions [1]. Similarly, Valentim A.F. and co-authors examined the influence of tongue pressure on dental arches at rest and during swallowing. They identified a correlation between tongue pressure and both the width and length of the dental arch [4].

Studies involving 3D biomechanical tongue models have been described in both international and Ukrainian scientific publications. Finite element models considering the nonlinear biomechanical behaviour of its tissues for assessing the impact of glossectomy on patients' speech were presented by Gérardim J.-M. and co-authors [7]. Calka M. conducted research in the context of speech motor control [8]. Perrier P. and co-authors studied biomechanical models of speech articulators for speech motor control, including examples where biomechanics informs us about trajectory shapes, the relationship between velocity and trajectory, the connection between motor control accuracy and acoustic variability, and the influence of dynamic properties on the shaping of soft speech articulators [9, 16].

The results of our experimental study demonstrate a clear trend in the localisation of maximum contact force (F, N) of the tongue on surrounding oral cavity tissues. The location of the zones identified in the experiment corresponds with data presented in other scientific publications [1, 4, 5]. It was clearly shown that enlargement of the tongue by 25% results in a significant static load on the surrounding bony structures. According to Wolff's law, increased contact pressure and stress within bone significantly influence its growth and remodelling. It was found that the most intensive pressure of the tongue develops in the frontal area of the maxilla and mandible; thus, a tendency towards sagittal anomalies in patients with macroglossia can be expected. This finding is supported by clinical studies in Angle Class III patients.

Although the absolute values obtained in the experimental study should not be considered definitive due to the lack of reference normative values, the data obtained can be used for the development of prevention strategies in patients with enlarged tongue, through compensation of abnormal forces and increasing space for the tongue by maxillary expansion or similar approaches.

To prevent distal displacement of the tongue within the lower jaw space, a barrier was placed. Without this barrier, the experiment was unsuccessful, as the tongue "protruded distally" and failed to apply measurable force to the sensor.

The accuracy of in vivo measurements is highly dependent on the method and location of sensor placement. Even when mounted on ultra-thin, custom-made overlays, sensors may introduce distortion into the results. Conversely, measurements taken without stable fixation are also suboptimal, as sensors may shift from the intended measurement site. Another critical factor influencing data reliability is the sensitivity of the device.

PROSPECTS FOR FURTHER RESEARCH

It is planned to identify the contact force (F, N) of the tongue, investigate the level of stress and on the areas of the oral cavity in the upper and lower jaws in vivo and conduct comparative analysis of the contact force indicators.

CONCLUSIONS

A comparative analysis of tongue contact force indicators obtained during the experimental study demonstrated an increase in values when the tongue volume was enlarged to 125% in the areas of the oral cavity of the upper and lower jaws, compared with the actual tongue volume. The areas of the marginal gingiva on the lingual surface of the lower central incisors, the marginal gingiva on the palatal surface of the upper central incisors, the middle third on the lingual surface of the lower central incisors, and the middle third on the palatal surface of the upper central incisors were the zones where the values were highest.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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A – Work concept and design, B – Data collection and analysis, C – Responsibility for statistical analysis, D – Writing the article, E – Critical review, F – Final approval of the article

RECEIVED: 15.01.2026
ACCEPTED: 22.05.2026