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Application of the Finite Element Method to the Analysis of Adaptive Transformations of the Jaw Apparatus of Fish

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Abstract

This paper presents the potential of modern visualization and numerical analysis approaches using the finite element method to study adaptive skeletal deformations in lower vertebrates. The functional analysis of the visceral skeleton of fish was based on the virtual reconstruction of dental CT data into finite element models using engineering design and modeling software (Femap, Nastran, Patran). Visualization of the stress-strain state of anatomical structures revealed that their transformation occurs at sites of maximum bone stress concentration and is a consequence of changes in force load during the development of the species' feeding strategy. Overall, the approach used facilitates a more comprehensive analysis of the functional foundations of skeletal structure and adaptive transformations for a given morphology of a particular species.

Keywords: fish, visceocranium, jaw apparatus, morpho-functional analysis, adaptation, stress-strain state (SSS), finite element model (FEM).

Introduction

Virtual reconstruction of the vertebrate skeleton, used for visualization and functional analysis of the object, makes it possible to extract more complete information about the biological role of the integral structure and the adaptive meaning of its transformations, which represents a significant addition to classical morphometric research methods. It is known that the leading factor determining bone tissue formation is mechanical loading, which changes during onto and phylogenesis [1, 2], indicating that adaptive “deformation” of bone occurs at sites of greatest stress. In this regard, the question of the localization and distribution of stresses and strains in an object of given shape remains open. One of the modern methodological approaches that allows us to approach the solution of this problem is the determination of the stress–strain state of bone tissue under the action of external forces. The most widely used mathematical method for strength analysis of structures is the finite element method, which makes it possible to identify stresses and strains in an object of any shape and geometry under specified loads and mechanical characteristics of the object under study. To date, the use of this approach has made it possible to perform virtual reconstructions of the skeleton of some species of large mammals and extinct reptiles, as well as to analyze aspects of their functional and evolutionary morphology [3, 17]. Based on the experience of previous researchers, we have developed and tested a method for step by step assembly of tomographic sections and the creation of a virtual construction of the fish skeleton, which al-

lows obtaining primary data on the mechanical behavior of bone tissue in this group of vertebrates [18, 19]. The present work is a continuation of the initiated research and is devoted to the application of the finite element method for the analysis of adaptive transformations of the fish jaw apparatus.

Creation and testing of the finite element model (FEM) of the fish jaw apparatus

The main stages of modeling the FEM of the fish viscerocranium were presented in detail in previous works [18, 19]. In the present study, in order to fully demonstrate the application of FEM for studying adaptive transformations of the fish jaw apparatus, we present an algorithm and a brief description of the main stages of model creation for testing (Fig. 1).

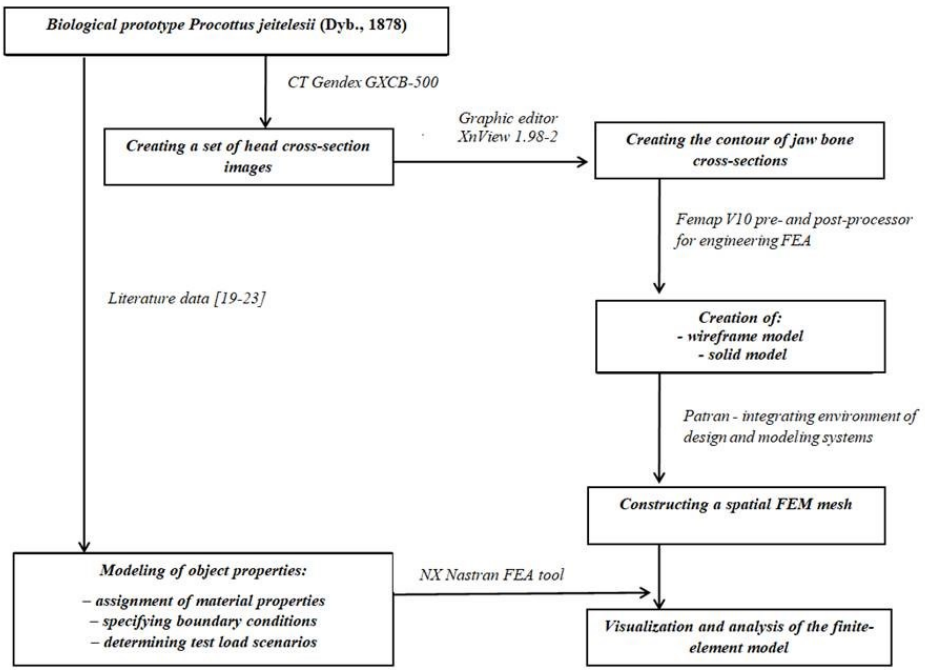


Fig. 1. Algorithm for creating and analyzing the FEM of the fish jaw apparatus [19].

Creation of the FEM of the fish jaw apparatus. The biological prototype of the model being created was a collection specimen of the Baikal endemic ichthyofauna – Procottus jeitelesii (Dyb., 1878). Scanning of the object was performed using a Gendex GXCB 50 cone beam volumetric tomography unit (https://angarsk-stomklinika.ru) in a vertical position, from the symphysis to the posterior edge of the operculum. The image frame parameters were 216 × 216 mm with a slice step of 0.4 mm. Visualization of the results of layer-by-layer scanning of the fish skull was carried out using iCATVision 1.8 software for visualization of computed tomography data of the maxillofacial region [20]. The source materials were raster images in JPEG format with a size of 312 × 312 pixels (Fig. 2 a). A total of 106 section images of the head were obtained and analyzed.

Analysis of the obtained sections was performed using a color RGB model in the XnView 1.98.2 image viewing and editing software [21]. The contours of the object were created by vectorizing points in the color gradient at the boundary between the background and the bone section (Fig. 2 a). For subsequent data processing in engineering analysis programs, the obtained section contour images were converted into DXF and NEU formats.

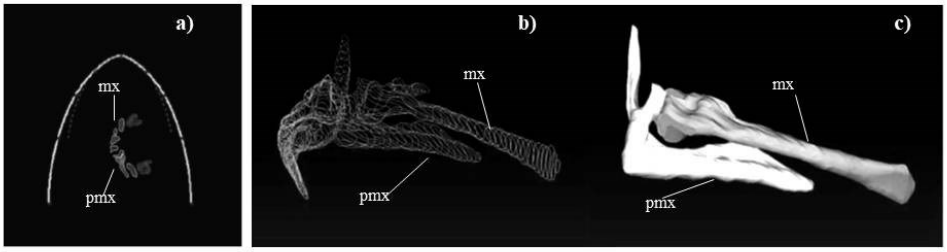


Fig. 2. Creation of a solid model of the maxillary bones of the fish (P. jeitelesii): a) bone contours in the raster image of CT sections of the head; b) wireframe model; c) solid model. Designations of the main elements: mx – maxilla, pmx – premaxilla.

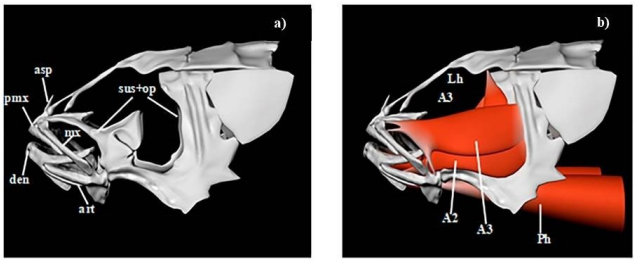


Fig. 3. a) Three-dimensional solid model of the fish viscerocranium (lateral view); b) Three dimensional osteomuscular model of the fish viscerocranium (lateral view). Designations of the main elements: Bones: art – anguloarticulare, den – dentale, mx – maxillare, op+sus – suspensorium + operculum complex, pmx – praemaxillare (asp – ascending process of the pmx). Musculature: A1, A2, A3 – portions of m. adductor mandibulare, Lh – m. levator hyomandibulare et arcus palatini, Ph – m. protractor hyoidei.

Assembly of section contours into a wireframe model was carried out in the Femap V 10 software [22] (Fig. 2 b). Using the geometric modeling command package (Parasolid, Standard), the wireframe models were transformed into solid counterparts (Fig. 2 c). The required elements of the viscerocranial bones and musculature were reconstructed based on visualization of fixed preparations of fish heads in the 3D modeling and animation software Autodesk Maya 2012 [23] (Fig. 3 a, b). The reliability of the geometric parameters of the resulting model was ensured by using morphometric data of the studied object. Generation of the finite element mesh in the solid model was implemented in the integrated environment of the design and modeling systems Patran [24].

Conditions for FEM testing. The main objective of this work was to determine and visualize the stress–strain state in an object of given shape, regardless of the properties of its material. The localization and direction of application of the test load were determined based on literature data characterizing the morphofunctional features of the fish jaw apparatus [25, 28]. Concentrated forces were applied at key nodes located at the attachment sites of the leading elements of the musculoligamentous apparatus of the head, as demonstrated on the osteomuscular virtual construction (Fig. 3 b). Additionally, loads simulating the pressure of prey on the tooth surface of the praemaxillare and dentale were modeled. The direction of the muscle force vectors was set according to previously obtained data from testing kinematic models of the fish jaw apparatus [29].

When assigning material properties, data on the mechanical characteristics of bone tissue of the frontal bone of reptiles (E = 5600 Pa – elastic modulus, ν = 0.29 – Poisson's ratio) were used, which is due to the lack of data on the mechanical characteristics of fish [19]. To identify zones of maximum stress and potential deformations, a minimum load (10 N per node) was applied to the model under study.

For the analysis of finite element models, a static calculation was performed using the solver in the Nastran software [30], taking into account the imposed boundary conditions and selected load variants.

Visualization and analysis of the stress–strain state of the FEM of the fish jaw bones

Based on the analysis of the SSS of the obtained objects, zones of potential adaptive deformations were identified for two positions of the oral apparatus: 1) “preparation for prey capture” (mouth opening and protrusion of the praemaxillare) and 2) “prey capture” (mouth closing) (Figs. 4, 5). Visualization of the SSS calculations was performed in the Patran environment, in accordance with a color scale characterizing the distribution of stress fields in the presented objects.

Position “Preparation for prey capture”: The mouth opening mechanism is ensured by the functioning of the opercular musculature, which acts through the l. mandibulo operculare on the dentale in the symphyseal region, causing its vertical downward displacement. The lower jaw block descends and moves the ventral ends of the praemaxillare and maxillare downward via the l. maxilla mandibulare anterius connecting to it. Through the A1 portion of the m. adductor mandibulae, a force is exerted on the cranial part of the maxillare, as a result of which it pushes forward the praemaxillare, which is movably articulated with the ethmoidal part of the neurocranium [25, 28]. The localization and distribution of the SSS during mouth opening for each of the jaw bones were as follows (Fig. 4):

- The *praemaxillare*, as a result of passive protrusion due to the action of the maxillare, experiences compressive stress in the zone of their direct contact (the articular process area);
- The *maxillare* experiences stress from axial force, which results from the action of the A1 portion of the *m. adductor mandibulae* attached near the articular head; the region of greatest stress is located in the compression zone (resistance to lateral bending), situated on the inner side of the bone;
- The *dentale* experiences local tensile stress in the attachment area of the l. *maxilla-mandibulare*, which lowers the lower jaw downward;
- The *anguloarticulare* experiences the greatest tensile stress at the base of the upper process, as a result of resistance to dorso-ventral bending of the lower process arising under the action of tensile forces from the *dentale* (contact between the *anguloarticulare* and the *dentale*).

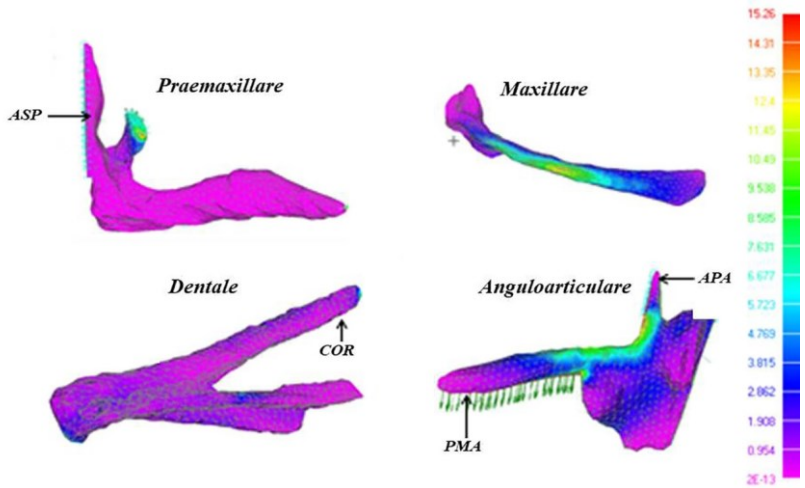


Fig. 4. Stress fields on the surface of the FEM of the jaw bones in the “mouth opening” position: Praemaxillare, asp – ascending process; Dentale, cor – coronoid process; Anguloarticulare, apa – upper process, pma – lower process. *Note*: green arrows indicate the localization and direction of the applied forces; light blue arrows indicate the boundary conditions.

Position "Prey capture": Mouth closing is accomplished by the complex of the m. adductor mandibulae, which originates in the postorbital region of the viscerocranium; further, the muscle bundles attach in the area of the upper process of the anguloarticulare (A2) and the coronoid process of the dentale (A1, A2, A3, and Aw). The adductor complex, acting on these processes, moves the lower jaw upward. As the lower jaw rises, it pulls the ventral ends of the praemaxillare and maxillare via the l. maxilla mandibulare anterius, returning them to their previous position [20, 23]. The localization and distribution of the SSS during prey capture and mouth closing for each of the jaw bones were as follows (Fig. 5):

- The *praemaxillare*, under the pressure of the held prey, experiences compressive stress in the horizontal plane of the bone, as a result of its resistance to lateral bending; the maximum compressive stresses are concentrated in the region of the upper process, which undergoes dorso-ventral bending;
- The *maxillare* experiences the same loads as in the previous variant, due to the action of similar forces;
- The *dentale* experiences maximum stresses in the region of the coronoid process, due to resistance to deformations of the "torsion" type, which result from the combined application of several multidirectional forces: compression from the tooth surface (resistance of the prey), tension of the process from the m. adductor mandibulae complex, and compression arising from the resistance of the lower process of the anguloarticulare;
- The *anguloarticulare* experiences the greatest bilateral stress at the base of the upper process, as a result of its resistance to dorso-ventral bending arising under the action of tensile forces from the A2 portion of the m. adductor mandibulae.

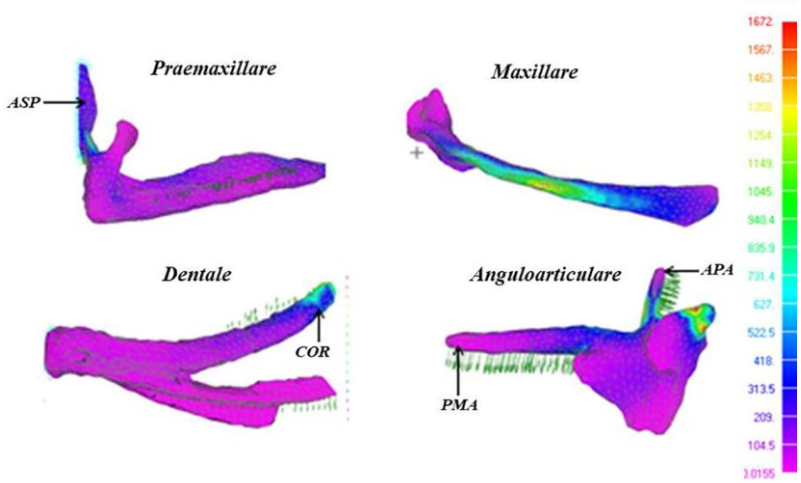


Fig. 5. Stress fields on the surface of the FEM of the jaw bones in the "mouth closing" position: Praemaxillare, asp – ascending process; Dentale, cor – coronoid process; Anguloarticulare, apa – upper process, pma – lower process. Note: green arrows indicate the localization and direction of the applied forces; lightblue arrows indicate the boundary conditions.

Functional analysis of adaptive transformations of the fish jaw apparatus based on FEM

Functional analysis of structural transformations of the feeding apparatus is inextricably linked to the issues of formation of the trophic strategy of a particular species. Analysis of numerous literature data shows that the leading trend in morphological variability within most fish families is the elongation of the jaws and reduction of mouth protrusion, which is associated with an increase in the size of food objects and a partial transition to ichthyophagy [30-35]. This trend was previously noted for a group of closely related species of coastal Cottoidei, demonstrating a consistent shift in trophic adaptation from benthophagy to ichthyophagy (in the direction: Paracottus knerii – Leocottus kesslerii – Batrachocottus baicalensis) [34]. Using graphical visualization of morphometric data of the jaw bones, the interrelated

variability of a number of morphogeometric parameters was revealed and demonstrated (Fig. 6). It was established that the main trend in the transition from benthophagy to ichthyophagy is the elongation of the jaws and a decrease in their horizontal parameters, in particular, a decrease in the height of the ascending process of the praemaxillare – AC (from 80.7 to 51.6 in % of bone length), a decrease in the angle between the plane of the anguloarticulare and its upper process – ∠CDA (from 88° to 66°), and a decrease in the height of the dentale – BC (from 43.4 to 35.4 in % of bone length) (Fig. 6). It is known that bone remodeling occurs at sites of greatest stress, which results from the action of the musculoligamentous apparatus [1]. The results of the present study are consistent with previously obtained data. As shown above, the maximum stress fields tend to concentrate in areas undergoing the greatest modification, in particular in the region of the jaw processes, which serve as attachment points for muscles and ligaments.

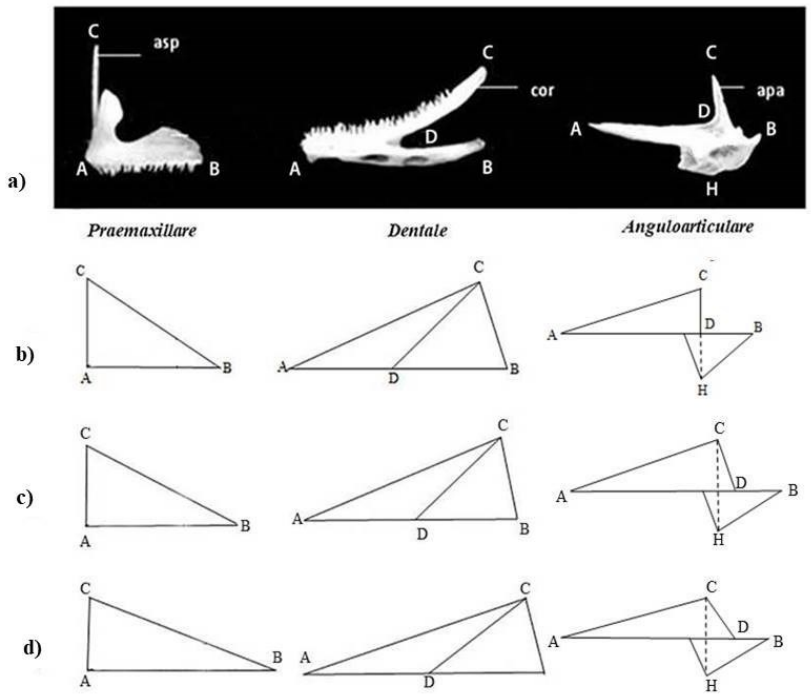


Fig. 6. Geometric projections of the jaw bones of Baikal sculpin fishes of the littoral group (Cottoidei): a) measurement scheme (in % of bone length); b) P. knerii; в) *L.kesslerii*; г) *B.baicalensis* [35]; *Designations:* Praemaxillare: asp – ascending process, (AB – bone length, AC – height of asp); Dentale: cor – coronoid process (AB – bone length, BC – height, AC – position of the posterior end of the coronoid process, DC – length of the coronoid process); Anguloarticulare: apa – upper process (AB – bone length, AD – position of the base of the upper process, CD – length of the upper process, CH – bone height, ∠CDA – angle formed by the upper process and the bone plane).

According to experimental data, for effective prey capture, the upper jaw of fishes is protruded forward, which occurs through the sliding of the ascending processes of the praemaxillare along the ethmoidal part of the skull [26-34]. It is evident that the maximum force load during prey capture falls on the ascending processes of the praemaxillare, analogous to the "redistribution of the foot's supporting load to concentration in the heel region." Accordingly, with the elongation of the praemaxillare and the "support" area in predators, the pressure on the ascending processes increases, which leads to their gradual reduction (Figs. 4-6).

With jaw elongation in ichthyophages, greater effort is required for mouth opening/closing [1]. This process is accomplished by the A2 and AW portions of the m. adductor mandibulae complex, which attach to the inner side of the body of the anguloarticulare and its upper pro-

cess [26, 27]. The increasing force load from the musculature leads to modification of the shape of the anguloarticulare. Thus, in the case of a “perpendicular” orientation of the process in benthophages, the forces of the m. adductor mandibulae A2 are unidirectional with the cross-section and act mainly on the longitudinal axis (Fig. 6). The successive deviation of the upper process toward the plane of the anguloarticulare during the transition to ichthyophagy leads to a redistribution of stress between its longitudinal and cross-sections due to their displacement relative to the direction of forces, and consequently reduces the risk of irreversible deformations under increased load (Fig. 5). The displacement of the upper process of the anguloarticulare into a horizontal position entails a decrease in the height of the dentale, which contacts it in the region of the coronoid process, experiencing a combined effect from the m. adductor mandibulae complex and the captured prey.

Conclusion

The development of methods for virtual reconstruction of anatomical structures makes it possible to visualize and reveal hidden patterns of transformation of the skeleton and its individual elements, which are not always evident when using classical morphometry. Of great interest in studying the adaptive variability of the jaw apparatus in various taxa of vertebrates is the functional analysis and visualization of the variability of the shape of skeletal structures and the prediction of their behavior under the action of external forces. In the present work, to solve the problem of the stress–strain state of the object, one of the modern mathematical approaches – the finite element method – was applied. The development and visualization of the FEM of the fish jaw apparatus enabled the visualization and identification of the localization of areas with the greatest stress under simulated loading conditions. Based on the obtained results, it was established that structural changes occur at sites of maximum bone stress concentration, with the jaw processes, which play a key role in the functioning of the fish oral apparatus, being subject to the greatest deformation. It is evident that the particular features of transformations of the jaw bones in different fish species are a consequence of the uneven action of force loads, which change during adaptation to feeding on different groups of organisms.

The results obtained at the current stage of the research require further development, in particular, the determination of the mechanical properties of fish bone material and its integration with the features of shape variability of the object under load.

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