Review article

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MUSCULOSKELETAL BIOMECHANICS IN THE HUMAN JAW

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Most computer simulations treat the mandible as a rigid or as a flexible beam acted upon by muscles capable of differential contraction, and predict dental and articular reaction forces at selected sites. The more advanced models employ finite element analysis to include estimations of local skeletal stress, strains and deformations. It seems certain that the jaw bends three-dimensionally in a complex manner when loaded by muscle action, and how it does so depends on the clenching task. In addition, compressive loads on the mandibular condyles vary with the bite point, and are unevenly distributed between them with asymmetric biting on the dental arches. The problem of morphological definition is difficult to overcome, since this varies so much between individuals, especially when accompanied by pathology. Variations in jaw motion are common too, making it hard to define normal patterns of behavior.

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Introduction

Muscle fibers generally attach directly to the bone, or to cylindrical, ovoid, or elongated tendons. Complex skeletal muscles often contain large internal aponeuroses to which muscle fibers attach, and it is common for these aponeuroses to differ in orientation and size within the same muscle. Fibers may lie parallel to the line of action of the muscle if it is simple, or at angles to its aponeuroses if it is complex. When one of the attachments is to a tendon sheath and the other to an area of bone, translation and rotation of both bone and aponeurosis are possible due to the action of an induced force couple (1). The relationship between the anatomical form of skeletal muscle, tensions during contraction, tendon properties, muscle shape, and local intramuscular pressures are not well understood. Conceptually, any interactions between these variables have usually been established by modeling.

In order to describe new knowledge about the structure and biomechanical properties of the musculoskeletal system, we used more recent literature (more than three-quarters of the references are from the last ten years). Older references were used to the extent that reflects knowledge that is still current in this area. Several databases were used for the literature search, and some references came from personal collection. All studies were potentially included, but we used only available data. In the literature review, we used original articles, retrospective studies, data from appropriate textbooks and a few review articles. The authors of some papers have used different biomechanical models, especially the finite element method (2).

Finite element analysis (FEA) has become a popular tool for simulating the effect of feeding loads on the skull. However, modeling the function of the masticatory system in a realistic way is a challenging task. One difficulty is to decide on specific values for the essential model properties because the literature often reports large ranges for these values and indeed sometimes they are unknown (3). Another difficulty is to decide on the degree of simplification of the model, because software and time limitations do not allow modeling of the masticatory system in all its known complexity. It is therefore not surprising that previous FEA studies of the masticatory apparatus differ significantly regarding basic input variables such as material properties, constraints, and applied forces (4)

Jaw mechanics

Computer simulation has emerged as a practical way to demonstrate the principles of muscle and jaw mechanics. It has been used to predict force distribution in the system, and to explain the relative contributions of variables such as muscle size and angulation to reaction forces at anatomical sites resisting the effects of muscle contraction (5).

The mandible as a rigid beam

A central assumption in many simulations is that the mandible is a rigid beam, acted upon by isometric muscle forces at key points, and resisted by reaction forces at other sites. Two-dimensional models can simulate bilaterally-symmetrical forces only, e.g., midline (incisal) bites or bite forces assumed to be equally distributed on both sides of the dental arch (6). All models are designed to solve the magnitude and/or direction of a number of unknown force vectors when others are specified. It is possible to assign likely tensions to all the muscles, and solve for reaction forces at the teeth and joints. Conversely, a modeler can place forces at the teeth and joints, then calculate muscle tensions and their levels of presumed activation (7). For example, coaxial, transverse forces acting through the mandibular condyles may have to be divided arbitrarily in different proportions between the right and left condyles (8).

Irrespective of how they are used, rigid beam models ensure that any forces which are not coplanar are made so by expressing them as vector components in two or three orthogonal planes, and that all translational forces and all torques about any axis sum to zero (9). Rigid beam models presently cope with presumed asymmetrical magnitudes and orientations of forces at both condyles by solving for single vectors at each condylar site. With few exceptions, bite point force is also represented by a single vector passing through some point in the dental arch (10). In fact, however, occlusal forces are usually multiple since dispersed contacts on cuspal facets have different orientations. Single-point bite forces are important oversimplifications in models, because any under-representation of non-parallel forces at the dental arch requires the introduction of compensatory forces and torques at condylar reaction sites.

In summary, it can be assumed that during normal functional loading of the dentition, bilateral, though usually asymmetrical, condylar loading occurs according to the side of the dental arch used (11). The magnitudes of these loads fluctuate with changing muscle tensions and bite forces, and the loads are usually directed at angles commensurate with the natural resistance provided by local anatomy during tooth clenching, condylar forces are developed which are aligned approximately perpendicular to the eminence when the jaw leaves the intercuspal position, and roughly parallel to occlusal plane, or more anterior than this when the condylar head is in the fossa. Under unusual conditions, perhaps involving unique combinations of musculoskeletal architecture, dental arch form, unilateral posterior tooth contact, and symmetric muscle contraction, it seems possible to apply traction to the articulation on the side of the bite point (12).

The mandible as a flexible beam

Finite element analysis (FEA) models of the jaw depend on the static equilibrium theory for their operation, but differ from rigid beam models because they permit analysis of physical changes within the system, which is considered to be elastic. This is accomplished by dividing the mandible and its articulation into its component tissues, e.g., cortical and cancellous bone, fibrous connective tissue, enamel, dentine, etc. The tissues are each represented by thousands of small geometric elements with unique elastic properties which may differ along element axes (13). Each element is connected to neighboring ones by nodes, thereby linking the entire system. When muscle force vectors are applied at optional sites, rigid boundary constraints introduced at others prevent the network from moving. The system deforms elastically in between, permitting detailed analysis of such properties as displacements, stresses, strains, element forces, and reaction forces (14).

FEA modeling has many advantages. The lower jaw behaves as an object capable of deforming in a nonlinear manner, copying its response in life. It does so under the influence of jaw muscle tensions which can be applied to wide areas of the bony cortex instead of isolated points. FEA models can be built for different purposes, e.g., to study the effects of different muscle activation strategies, altered musculoskeletal morphology, the design and probable behavior of prosthetic and surgical procedures. They can also be used to evaluate devices, implants or other biomaterials (15).

Conclusion

Most computer simulations treat the mandible as a rigid or as a flexible beam acted upon by muscles capable of differential contraction, and predict dental and articular reaction forces at selected sites.

The more advanced models employ finite element analysis to include estimations of local skeletal stress, strains and deformations. It seems certain that the jaw bends three-dimensionally in a complex manner when loaded by muscle action, and how it does so, depends on the clenching task. In addition, compressive loads on the mandibular condyles vary with the bite point, and are unevenly distributed between them with asymmetric biting on the dental arches. The problem of morphological definition is difficult to overcome, since this varies so much between individuals, especially when accompanied by pathology. Variations in jaw motion are common too, making it hard to define normal patterns of behavior.

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MUSKULOSKELETALNA BIOMEHANIKA LJUDSKE VILICE

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Većina kompjuterskih simulacija tretira mandibulu kao krutu ili kao fleksibilnu gredu na koju deluju mišići sposobni za različite oblike kontrakcija i predviđaju efekte sila na zube i temporomandibularni zglob. Napredni kompjuterski modeli koriste metode analize konačnih elemenata u objašnjenju lokalnih stresnih uticaja na skeletni i mišićni sistem. Pretpostavlja se da se donja vilica savija trodimenzionalno, na složen način pod dejstvom mišića, zavisno od mesta delovanja sile stezanja. Pored toga, kompresivna opterećenja na mandibularnim kondilima variraju sa tačkom zagriza, u kom slučaju su neravnomerno raspoređena na zubnim lukovima. Problem morfološke definicije teško je prevazići, jer se veoma razlikuje između pojedinaca, posebno kada se utvrde patološki procesi. Varijacije u kretanju vilice su uobičajene, pa je teško definisati normalne obrasce ponašanja.

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Ključne reči: *temporomandibularni zglob, pokreti u temporomandibularnom zglobu, artikulacija viličnog zgloba*