# Povijesni razvoj biomehanike

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Sažetak

*Biomaheniku možemo odrediti kao znanost koja zakone mehanike primjenjuje u rješavanju biologijskih probelma proučavajući mehanička svojstva bioloških organizama, sustava organa ili tkiva.*

*Biomeahnička se istraživanja rabe u svim granama medicine. Povijest biomehanike nije moguće odijeliti od povijesnoga razvoja mehanike, a niti od razvoja biologije i medicine u cjelini.*

Ključne riječi: *biomehanika, povijesni razvoj*

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Multidisciplinaran karakter biomehanike, što zadire u raznovrsna područja biologijskih, fizičkih, mehaničkih, tehničkih te temeljnih i kliničkih znanosti humane i veterinarske medicine, okuplja istraživače mnogih i različitih struka. Zato je vrlo teško dati sveobuhvatnu i za sve prihvatljivu definiciju biomehanike (1).

Biomehaniku ipak najsažetije i najjednostavnije možemo odrediti kao znanost koja zakone mehanike primjenjuje u rješavanju biologijskih problema proučavajući mehanička svojstva bioloških organizama, sustava, organa ili tkiva.

Dvije znanosti - biologiija i mehanika - udružuju se u posve novu struku koja u biti nije jednostavna primjena mehanike u biologiji niti biologije u mehanici, nego je sinteza obiju znanosti. Pri tome udio pojedine struke ovisi o području ili o konkretnom problemu što se proučava (2).

Područje biomehanike nije jedinstveno formulirano i nije ga moguće ograničiti. Razlog je tomu u činjenici da se biomehanička istraživanja mogu upotrabiti u svim granama medicine, budući da su fizikalne znanosti i reakcije duboko utkane u svakome živom tkivu.

U eksperimentalnim istraživanjima i u kliničkoj primjeni udio je biomehanike ograničen uglavnom na kruta tkiva i lokomotorni sustav. Razlog tomu je veća mogućnost primjene fizikalnih zakonitosti i matematičkog izračunavanja što je u lokomotornom sustavu, napose njegovim krutim djelovima, mnogo veća nego u kojim drugim organima (3).

Povijest biomehanike nije moguće odijeliti od povijesnoga razvoja mehanike, te razvoja biologije i medicine. Prve empirijske spoznaje o zakonitostima mehanike i o povezanosti mehanike i živih organizama potječu jamačno iz pretpovijesti.

Čovjekovo zanimanje za oblik i proporcije ljudskog i životinjskoga tijela u mirovanju ili u pokretu staro je koliko i čovjek. Oduvijek su kretanje i plivanje životinja, let ptica, te oblik i pokretanje čovjekova tijela zanimali ljude - od umjetnika i filozofa pa do liječnika, fizičara i tehničara. Za one prve promatranje oblika i gibanja živih bića vrhunski je estetski doživljaj, a za druge isti oblici i pokreti savršenstvo funkcionalnosti i ekstremna racionalnost oblika. Teško je reći je li čovjek prije shvatio u svojoj ruci funkciju poluge ili je izmislio polugu vidjevši nesavršenost uporabivosti ruke.

Tijelo normalnoga čovjeka proporcionalno je sazdano, a te su proporcije rezultat biomehaničke funkcijske prilagodbe tijekom evolucije.

Već i najstariji špiljski crteži svjedoče o čovjekovoj izvanrednoj sposobnosti zapažanja. Sva oruđa i oružja za lov i rat nastala su, barem djelomice, kao rezultat biomehaničkih iskustava. Važne podatke za povijest biomehanike nalazimo u pisanim spomenicama pradavnih civilizacija (Ebersov i Smithov papirus).

Otkrića i spoznaje antičkih filozofa, matematičara, fizičara i prirodoslovaca (Aristotel, Arhimed, Pitagora, Heron) utjecala su na gledišta pojedinih liječnika toga doba koji su zakonima mehanike nastojali protumačiti različite medicinske pojave (Erazistrat i Asklepije) ili primijeniti zakone mehanike u liječenju iščašenja i lomova kostiju (Hipokrat i Galen).

Aristotel je u svojim djelima sabrao sva znanja svojega doba o problemima u svezi s mehanikom.

Arihmed je u IV. st. pr. Krista jasno i točno postavio zakon poluge.

Erazistrat je pridonio razumijevanju krvnog optjecaja, te je opisao srčane zalistke i zaključio kako oni poput ventila osiguravaju jednosmjeran protok krvi.

Među rimskim liječnicima zaslužnim za razvoj biomehanike posebice se ističu Celzus i Galen. Galen je shvatio ovisnost nastanka ozljeda o načinu djelovanja sile na organizam i razvio je fizikalnu medicinu.

U razdoblju renesanse odbacuju se dogmatska shvaćanja i to je omogućilo ponovni razvoj prirodnih znanosti. Spoznaje se temelje na zapažanjima prigodom raščlambe ljudskoga tijela, u čemu s posebice ističe Andreas Vesalius.

Leonardo da Vinci proučavao je let ptica, kretanje čovjeka i životinje. Secirao je ljudsko tijelo, izučavao anatomiju lokomotornoga sustava, rad skeletnih mišića i rad srca, te mehaniku disanja, povezujući u jedinstvnu cjelinu spoznaje iz anatomije i mehanike. Bio je začetnik bionike, koje je moto: "Živi su prototipovi ključem nove tehnike".

Galileo Galilei (4) jedan je od ključnih utemeljitelja moderne mehanike. Odredio je zakon gibanja i načelo inercije, a prvi je izmjerio frekvenciju bila te razmatrao mehaničke utjecaje gibanja na oblik i veličinu kostiju.

René Descartes je, služeći se zakonima mehanike, tumačio funkcije čovjekova organizma i ustvrdio da je čovjek mehanički stroj kojemu je pridodan duh, što ga razlikuje od životinje jer mu daje misaonu sposobnost.

William Harvey je temeljem mjerenja i matematičke logike godine 1828. otkrio i protumačio krvotok, a pokazao je i da krv može izlaziti iz srčane klijetke samo jednosmjerno, te da se srce kontrahira 72 puta u minuti.

Gianalfonsa Borellija pak smatramo začetnikom biodinamike i biokinetike. Godine 1680. u svojem je djelu "De motu animalium" (5) analizirao kretnje tijela i hod, mišićnu djelatnost, let ptica, plivanje riba, crijevno gibanje, srčani rad itd.

Isaac Newton je definirao silu, a godine 1687. u djelu "Philosophia naturali principia mathematica" obznanio svoja tri povijesna aksioma.

Liječnik i fizičar Robert Hooke postavio je zakon o proporcionalnom suodnosu sila i deformacija elastičnoga tijela.

Naš znanstvenik iz Dubrovnika Marin Getaldić u to se je vrijeme bavio određivanjem odnosa između težine i obujma raznih tijela.

Dubrovčanin Đuro Baglivi je godine 1696. objavio knjigu "De praxi medica" u kojoj su vrlo slikovito prikazani pojedini organski sustavi. Tako, primjerice, čeljusti i zube uspoređuje s kliještima, želudac s posudom, vene i arterije s hidrauličkim cijevima, srce s crpkom i sl.

Exupere Bertin secirao je čovjeka koji je pokušao ubiti kralja Louisa XIV. te su atentatora zato rastrgnuli konjima. Opisao je iliofemoralnu svezu i zapazio je da je ta sveza bila jača na vlak od susjednih kostiju jer je ostala čitava dok su okolne kosti bile slomljene.

U 19. stoljeću počinju važna anatomska istraživanja, a to je razdoblje važno i po kauzalnom i funkcionalnom pristupu u proučavanju tijela. Pri kraju stoljeća nastaje i poznati Rouxov zakon o funkcijskoj prilagodbi kosti (6).

Prva eksprimentalna istraživanja čvrstoće kosti uz određivanje modula elastičnosti proveli su Gustav Wertheim 1847. i August Rauber 1876. godine.

F. O. Ward (7) je godine 1838. prikazao trokutasto područje razrjeđenja u trabekularnoj strukturi spužvaste kosti proksimalnoga kraja bedrene kosti (Wardov trokut), a G. H. Mayer (8) je 1867. potanko opisao trajektorijalnu građu spužvaste kosti.

Utemeljitelj suvremene europske biomehanike pokretačkoga sustava i ortopedske biomehanike jest Friedrich Pauwels (9).

U nas se biomehanika razvila u sklopu anatomije i kliničkih struka, posebice ortopedije i traumatologije.

Drago Perović (10,11,12) proveo je mnogobrojna istraživanja u području funkcijske anatomije, posebice funkcijske anatomije i aerodinamike dišnih putova. Originalna su njegova zapažanja o pneumatizaciji paranazalnih sinusa i "pneumatizacijskom stroju". Otkrio je i razjasnio značenje dotad nepoznatih tvorbi na stražnjemu dijelu nosne pregrade u području vomera koje je nazvao "aerodinamičkim adaptacionim tvorbama".

Ante Šercer i Jelena Krmpotić-Nemanić (13) istraživali su posljedice procesa pregibanja lubanjske baze, te su biomehanički protumačili nastanak devijacije nosne pregrade i nastanak otoskleroze.

Osobite zasluge za razvoj biomehanike primijenjena na lokomotorni sustav ima Ivo Ruszkowski (3,21). On je osim s mnogim liječnicima posebno razvio blisku suradnju sa znanstvenicima tehničkih struka Antunom Vučetićem, Osmanom Muftićem i drugima, pa danas možemo govoriti o zagrebačkoj biomehaničkoj školi.

Prilagodbene promjene nastale kao reakcija na izmijenjene mehaničke uvjete pri usporavnome položaju tijela i dvonožnom čovjekovu hodu, koje su vidljive u području kralješnice i zdjeličnog obruča, proučavali su: Jelena Krmpotić-Nemanić, M.Hudec, P.Keros, V.Nikolić, A.Jo, J.Hančevič, I.Vinter, S. Vukičević (14,15,16,17,18,19,20).

Sustav u čovječjevm organizmu, osim koštanoga na koji se biomehanička istraživanja najviše primjenjuju, jamačno je stomatognatni sustav.

Izvanredno složeno stvoren kostur lubanje i napose kostur lica imaju mnoge i različite funkcije. Mozgovni dio kostura glave okružuje veliki i mali mozak s mozgovnim deblom i svim pridruženim tvorbama. Ujedno se u razvijenim brojnim šupljinama kostura glave nalaze i četiri osjetila, te početni dijelovi dišnoga i probavnoga sustava, mnogobrojni mimični i žvačni mišići, fascije i vezivne tvorbe, krvne i limfne žile, živci i druga tzv. meka tkiva. Cijeli taj opsežni uređaj mora održavati ravnotežu odnosa pri promjenama u tijelu te osim zadaće žvakanja ima i mnoga značajna djelovanja. Spomenimo oblikovanje zalogaja, gutanje, tvorbu glasa, govor i pjevanje, sisanje, puhanje i zviždanje, te disanje na usta.

Značenje biomehaničkih proučavanja to je veće što su dijelovi orofacijalnoga kostura, premda je riječ o koštanoj tvari, organi podložni znatnim promjenama u vrijeme razvoja, ali i tijekom života. Mnoštvo morfologijskih značajki nastaje utjecajem unutrašnjih i izvanjskih čimbenika na već oblikovani orofacijalni kostur. Baš u tome veliko značenje imaju mehančke sile. Na mjestima djelovanja tih sila koštano tkivo reagira pregradnjom, te nastaju nova građa i oblici koji pridonose prilagodbi opterećenjima i fiziološkom djelovanju stomatognatoga sustava. Zato istraživanja biomehaničkoga ponašanja kostura lica, osim u stomatološkoj morfologiji, imaju i važnu praktičnu primjenu u kliničkoj stomatologiji sa stajališta funkcijske morfologije i suodnosa te razvoja i funkcijske međuovisnosti kostura lica, čeljusti, pa i čitava tijela.

C. Gorke (22), A. Richter i A. Benninghoff (23) već su početkom stoljeća nastojali utvrditi mehaničku svojstva i ponašanje kostura glave. Pri tome je Benninghoff (23) godine 1926. upozorio na istančanu građu zbite koštane tvari u lubanjama ljudi, koju je utvrdio postupkom otcijepa ili kalanja. Time je utvrđena činjenica da crte krtoga loma ili kalanja otkrivaju "trajektorije naprezanja" koji nastaju djelovanjem mehaničke sile prigodom žvakanja.

Crte krtoga loma na kosturu lica potanko je istraživao i Tappen (24) posebnim minutnim postupkom.

Banri Endo (25,26) ističe da kostur lica valja shvatiti kao složen sustav kojega se koštane prijenosnice naprezanja usredotočuju u smjerovima djelovanje žvačnih sila, ali i oko prirodnih otvora lubanje, uzdušnih paranazalnih šupljina itd.

Zagrebačka je biomehanička škola pak iznjedrila u ovome području niz stručnjaka koji su svojim djelima dali znatan prinos poznavanju biomehanike orofacijalnog sustava (7,28,29,30,31).

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# Sources for the History of Biomechanics

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Summary

*Biomechanics may be defined as a science which applies the laws of mechanics in solving biological problems, through studying mechanical characteristics of biological organisms, systems of organs or tissues.*

*Biomechanical research is used in all medical fields. The history of bimechanics cannot be viewed separately from the historic development of mechanics or from overall development of biology and medicine.*

Key words: *biomechanics, historic development*

The multidisciplinary character of biomechanics, which includes various areas of biological, physical, mathematical, technical and basic clinical sciences of human and veterinary medicine, brings together experts and researchers of various professions. It is therefore difficult to produce a comprehensive definition of biomechanics that would be acceptable to all (1).

The most concise and simplest way is to define biomechanics as a science that applies the laws of mechanics in the solving of biological problems, through studying mechanical properties of biological organisms, systems, organs or tissues.

Two sciences - biology and mechanics, are joined in an entirely new profession that in its essence cannot be define as simple application of mechanics to biology, or biology to mechanics, but rather as a synthesis of both these sciences. Here the participation of each individual profession depends on the particular area or concrete problems that are to be studied (2).

The field of biomechanics is not uniformly defined and it cannot be strictly limited. The reason lies partly in the fact that biomechanical research may be used in all medical specialities, as physical laws and reactions are profoundly incorporated in each single living tissue.

In experimental research and clinical application the participation of biomechanics is mostly limited to hart tissues and the locomotor system. It is probably so because there is a greater possibility of applying physical laws and mathematical models to the locomotor system, especially to its hard structures than to any other organs (3).

The history of biomechanics cannot be discussed separately from the historical development of mechanics and the development of biology and medicine. The initial empirical knowledge about laws of mechanics and connection between mechanics and living organisms certainly originate from prehistoric times.

The intereset of man in form and proportions of human and animal bodies at rest or in movement is as old as human history. Since time immemorial humans have been interested in the movement and swimming of animals, in the flying of birds, and in the form and motion of the human body - from artists and philosophers to physicians, physicists and technicians. For the former, the observation of form and motion of living creatures represents the highest aesthetic experience, while for the latter the same forms and motions are perfection of functionality and extreme rationality in forms. It is hard to say whether man first recognised the function of a lever in his hand or if he invented the lever after having realised the imperfection of his hand.

The body of a normal man is proportionately built, and these proportions are the result of biomechanical functional adjustment in the course of development (evolution).

Even the oldest cave drawings are evidence of man's extraordinary ability for perception. All hunting and fighting tools and weapons were at least partially designed as a result of biomechanical experience. Information, important to the history of biomechanics, may be found in written monuments of ancient civilisations (Ebers and Smith papyruses).

The discoveries and knowledge of ancient philosophers, mathematicians, physicists and biologists (Aristotle, Archimedes, Pitagora, Heron) had significant impact on the attitudes of many physicians of those times, who spared no effort to explain various medical phenomena (Erasistratus and Asklepios) or to apply the laws of mechanics in the treatment of dislocations and bone fractures (Hippocrates and Galen).

In his work Aristotle collected all knowledge of his time on the problems of mechanics.

Archimedes clearly and precisely formulated the law of the lever in the 4th century BC.

Erasistratus contributed to the understanding of blood circulation. He described heart valves and concluded that similar to a mechanical valve, they ensure a balanced and constant flow of blood.

Among the Roman physicians merit for the development of biomechanics is due to Celsus and Galen. Galen noticed that the occurrence of injury depended on the mode in which a force acts upon an organism and the also developed physical medicine.

During the Renaissance old dogmas were rejected and such a course of events enabled new development of natural sciences. Basic knowledge was gained through anatomical sections of the human body and Andreas Vesalius, a Flemish anatomist, had an outstanding role in this.

Leonardo da Vinci studied flying of birds and human and animal movement. By sections of the human body he analysed the anatomy of the locomotor system, action of skeletal muscles and the heart, and also the mechanics of breathing, integrating his findings into unique knowledge about anatomy and mechanics. He was a predecessor of bionics, the motto of which is: "Living prototypes are keys to new techniques."

Galileo Galilei (4) is one of the crucial founders of modern mechanics. He defined the law of motion and principle of inertia. He was the first to measure pulse frequency and to study mechanical influences of motion of the shape and size of bones.

René Descartes explained the functions of the human organism on the basis of laws of mechanics and he defined man as a mechanical machine to which spirit was added to make him different form animals, for it gives man his mental capacity.

In 1822 William Harvey revealed and explained blood circulation, based on measurements and mathematical logic. He showed that blood may leave the heart atrium only in one direction and that the heart contracts 72 times in a minute.

Giovanni Alfonso Borelli is considered the father of biodynamics and biokinematics. In 1680 in his work "De motu animalium" (5) the analysed motions of the body and walking, muscle activity and flying of birds, swimming of fish, intestinal peristalsis, heart action, etc.

Sir Isaac Newton defined force, and in 1687, in his work "Philosophiae naturalis principia mathematica", he enunciated his three historic axioms.

The physician and physicist, Robert Hooke, established the law on proportional correlation between forces and deformation of elastic body.

At that time Marin Getaldić, a Croatian scientist from Dubrovnik, was involved in determination of the relationship between weight and volume of various bodies.

Đuro Baglivi, a physician from Dubrovnik, in 1696 published a book "De praxi medica" in which he vivdly illustrates individual organic systems. For instance, he compares jaws and teeth with pincers, stomach with a vessel, veins and arteries with hydraulic tubes, heart with a pump, etc.

Exupere Bertin performed anatomic section on the body of a man who had attempted to murder King Louis XIV and was afterwards lacerated by horses. Bertin described the iliofemoral ligament and noticed that it resisted the pulling force better than the surrounding bones because it did not rupture, while the bones around it were broken.

The 19$^{th}$ century is characterised by the beginning of significant anatomic studies known for their causal and functional approach in the analysis of the human body. By the end of the century the famous Roux law had been established on functional adjustment of bones (6).

The first experimental studies about bone strength and determination of elesticity module were performed by Gustav Wertheim in 1847 and August Ruber 1876.

In 1838 E.O.Ward (7) identifed triangular regions of decreased density within the trabeculae of femoral neck spongy bone (Ward's triangle), while G.H. Meyer (8) described in 1867 trajectorial structure of cancellous bone.

Friedrich Pauwels (9) is considered the founder of European biomechanics of the locomotor system and orthopaedic biomechanics.

In Croatia biomechanics has developed as a part of anatomy and clinical medical specialities, orthopaedics and traumatology in particular.

Drago Perović (10,11,12) performed many studies in the field of functional anatomy especially functional anatomy and aerodynamics of respiratory pathways. Original observations made by Perović refer specifically to pneumatisation of paranasal sinuses and the "pneumatisation machine". He identified and explained the meaning of, until then, unknown structures within the posterior part of the nasal septum in the region of vomer, and he called them "aerodynamic adjustment structures".

Ante Šercer and Jelena Krmpotić-Nemanić (13) studied the results of the bending process of the cranial base and gave a biomechanical explanation of why deviation of the nasal septum and otosclerosis occur.

Special merit in the development of biomedhanics, especially its application to the locomotor system, is due to Ivo Ruszkowski (3,21), who established close co-operation with scientists in technical professions, so that today we may speak of the Zagreb School of Biomechanics.

Adjustment changes developed as a response to the altered mechanical conditions in an upright position of the body and human bipedal walking. These changes are particularly pronounced in the spinal region and pelvic girdle. They were studied by Jelena Krmpotić-Nemanić, M. Hudec, P. Keros, V. Nikolić, A. Jo, J. Hančević, I. Vinter, S. Vukičević (14,15,16,17,18,19,20).

Beside the osseous system, the stomatognathic system is another human body system to which biomechanical research has been applied to a great extent.

The extremely complex structure of the cranial skeleton, especially the facial one, protects the cerebrum and cerebellum with brain stem and all adjacent structures. At the same within many cavities of the skull there are four senses and initial parts of the respiratory and digestive systems, together with numerous mimic and mastication muscles, fascia, connective supportive structures, blood and lymph vessels, nerves and other so-called soft tissues. The entire apparatus must maintain properly balanced relations when changes in the body take place, so that beside the mastication role, it performs many other important functions. For instance, formation of bolus, swallowing (deglutition), production of sound and speech (phonation), singing, sucking, blowing, whistling, breathing by mouth.

The significance of biomechanical studies is even greater in view of the fact that part of the orofacial skeleton, despite its being bone matter, are organs susceptible to marked changes in the course of growth and development and also through the entire life. The multiplicity of morphological features result from the influence exerted by internal and external factors upon the already formed orofacial skeleton. It is here indeed that mechanical forces play their major role. At sites where these forces act osseous tissue responds by formation of partitions and in this way new structures and forms are created that facilitate adjustment to loads and physiological action of the stomatognathic system. Hence the study of biomechanical behaviour of the facial skeleton, apart from dental morphology, has an important practical role in clinical dentistry from the viewpoint of functional morphology and inter-relations, and the development of functional inter-relations in the facial skeleton, jaws and the entire body, by influence the position of teeth and enabling correct chewing and speech.

As early as the beginning of this century C. Gorke (22), A. Richter and A. Benninghoff (23) made efforts to determine mechanical properties and behaviour of the skull. In 1926 Benninghoff (23) warned of intricate structure in dense bony matter in human skulls that the defined on the basis or splitting of splintering procedures. In this way it was possible to realise that the lines of dry (closed) fracture of splintering reveal "tensile trajectories" resulting from action of mechanical forces during mastication.

Tappen (24) performed a detailed study of the lines of dry fracture in the facial skeleton by special minute procedure.

Banri Endo (25,26) is of the opinion that the facial skeleton should be understood as a complex system, the tensile trajectories of which are focused in directions in which the mastication forces act, but also around the natural apertures of the skull, along the paranasal cavities, etc.

The Zagreb school of biomchanics has produced many experts in the field who have significantly contributed to the knowledge of biomechanics of the orofacial system (27,28,29,30,31).