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Review

Biomechanics in Orthopaedics

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Abstract

In clinical orthopaedics, an approach based on biomechanical knowledge is a prerequisite. Studies on load distribution, gait analysis and implants have been extensively published aiming to aid clinicians in the processes of decision making and evaluation of treatments prior to using them in clinical practice. However, despite powerful scientific methods, the relevance of biomechanical studies with clinical orthopaedics, the adaptability and tolerance of living tissue, and the impact of these studies for clinical practice is debatable. Indeed, these studies may have limited clinical relevance unless they account for important parameters such as biological behaviour, tissue tolerance and adaptability. This article summarizes the history of biomechanics in orthopaedics, and discusses the clinical relevance of biomechanical studies in orthopaedic and trauma surgery.

Key words: Biomechanics; Orthopaedics; Tissue; Tolerance; Adaptation.

History of Orthopaedic Biomechanics

Biomechanics aims to enlighten into the mechanics of tissue function, failure or injury, and to provide information on the most effective and safe motion patterns and exercises to improve movement, and how professionals might improve movements, implants or osteosyntheses [1]. The word biomechanics originates from the Ancient Greek "βίος" (life) and "μηχανική" (mechanics), and refers to the study of the mechanical principles of living tissue, particularly their movement and structure and how forces create motion [2]. The roots of biomechanics date back to Greek antiquity. Hippocrates of Kos (460-370 BC), a Greek physician of the Age of Pericles, referred to as the Father of Western Medicine, wrote on many pragmatic treatments of common ailments such as bone fractures, joint dislocations and articular cartilage injuries, and promoted the application of mechanics (force and motion) to reduce dislocated knees and straighten spinal deformities [3, 4]. Aristotle of Stagira, Chalkidice (384-322 BC), a Greek philosopher who studied at Plato's Academy, was the first who studied on physiology and animal motions; many of his ideas on animals, physics and other scientific topics laid the broad foundations of the biological and physical sciences that were not to be superseded for nearly 2,500 years [4-6].

The discipline of biomechanics arose in the 16th century with the investigations of Galileo Galilei and the studies of Giovanni Alfonso Borelli on the forces imposed on human and animal bodies by the activities and functions of life; they were the first who recognized the relationship between the mechanical environment and living tissue responsiveness (adaptation) [7, 8]. The studies of Dr. YC Fung, referred to as the Father of Modern Biomechanics, contributed to a crescendo of biomechanics during the mid-1960s [9-11]. By the beginning of the 1970s, growth of the field accelerated; scientists from many different disciplines such as kinesiology, engineering, physics, biology, zoology and medicine including orthopaedics have been interested in biomechanics

[12]. Since then, several studies allowed for biomechanics to become a recognized specialization in science, and for the biomechanical principles to become systematically applied [13-15].

The word orthopaedics originates for the Ancient Greek "ὀρθὸς" (straight) and "παιδίον" (child); it was coined by the French doctor Nicholas Andry in 1741 [3,4]. Until the 20th century, orthopaedic doctors were mainly involved in straightening scoliotic spines, performing fracture fixation with braces and plaster casts, treating infections of the bone and joints, and other nonoperative procedures. With the development of modern orthopaedic surgical techniques and durable implants, orthopaedic surgery has greatly evolved. At that time, orthopaedics joined with biomechanics in a concerted effort to improve orthopaedic surgery [4]. Currently, orthopaedic biomechanics is a basic scientific and engineering discipline that is robust, vital, and dynamic [1, 4].

Biomechanics in Clinical Orthopaedics

Clinical biomechanics is defined as the application of mechanical principles to the management of clinical problems. In orthopaedics, this implies that biomechanics should be applied in clinical orthopaedics. Much research and published studies have improved the understanding of the mechanical principles involved in musculoskeletal disorders. However, it is difficult to adapt all information obtained with mechanical studies in tissue, even living tissue, to clinical practice [18]. Clinical orthopaedic biomechanics should cover the biomechanical aspects, etiology, diagnosis, treatment and prevention of a musculoskeletal disorder, and should involve a scientific approach to develop novel medical applications, with emphasis on scientific integrity and clinical relevance [18].

In clinical orthopaedics, an approach based on biomechanical knowledge is a prerequisite. While most biomechanical knowledge is not perfect and can only be organized into some general principles, it is much better at informing professional practice than merely using information, opinions or data with no implied degree of accuracy [1]. To gain new knowledge, one must start from a domain of generally accepted and accumulated prior knowledge. Most of the accumulated biomechanical knowledge is obtained by routine experiments and analyzed by well-accepted theories. However, with the accretion of knowledge, conflicts, inconsistencies and new hypotheses will arise. Each new hypothesis needs to be validated, and each new paradigm needs to overcome an existing theory or paradigm in a logical and rational way before it can be accepted and generally used by scientists and engineers [4]. For biomechanical studies, validity requires a context of adaptation and tissue material clarification, and clinical relevance.

Tissue in Orthopaedic Biomechanics

Four types of tissue exhibit properties which are different and probably non-interpretable in biological terms: (1) viable tissue *in situ* with no necrosis, (2) viable tissue *in vitro* maintained in a suitable medium and at body temperatures, (3) nonviable (dead) tissue maintained in some sort of medium and at body temperatures, and (4) nonviable tissue maintained moist, but either dried or cooled at some time [19]. Although cadaveric tissues are the gold standard simulators, they suffer from major drawbacks, including the risk of disease transmission, high cost, and prolonged preparation time [20]. Furthermore, cadaveric bone tissue disproportionately represent the elderly population whose bone quality may not be representative of most of the orthopedic population [21]. Accordingly, cadaveric tissue may not accurately represent the behavior of osteosynthesis constructs and orthopaedic implants in young, healthy patients with fractures. Furthermore, there is a high degree of variation in biomechanical properties between cadaveric tissues, reportedly up to 100% of the mean in some parameters [22]. The use of traditional formalin-based embalming solutions may excessively stiffen soft tissues [23]. Recently developed embalming solutions may preserve cadaveric tissue characteristics, but they are expensive and require even more specialized storage of specimens under vacuum refrigeration [23, 24]. Cost-effectiveness is a major concern in research. Any measure requiring new concepts will be easier to introduce in clinical practice if it has been previously validated with a biomechanical study. However, cost-effectiveness does not directly relate to medical efficacy, and can be the cause for clinical failure of biomechanical measures. Cost-effectiveness will become increasingly more important in the application of new measures. The measuring tools in biomechanical studies should reduce costs by eliminating unnecessary treatment or by identifying conditions early and avoiding expensive complications [25].

Cadavers, even though they are fixed in embalming chemicals, may still pose infection hazards. Infectious pathogens in cadavers at risk for disease transmission include *Mycobacterium tuberculosis*, hepatitis B and C viruses, HIV, and prions that cause transmissible spongiform encephalopathies [26-28]. In general, the risk of *Mycobacterium*

tuberculosis transmission is decreased by fixation. However, it has been shown that bacilli remain viable and infectious for at least 24 to 48 h after an infected cadaver has been embalmed [28]. Specific serologic markers of hepatitis B and C viruses can be detected in cadaveric tissue banks (hepatitis B surface antigen, 18.1%; hepatitis C antibody, 14.3%) [27, 29]. Infectious HIV has been reported in pleural fluid, pericardial fluid, blood, bone fragments, spleen, brain, bone marrow, and lymph nodes of such deceased patients after storage at 2°C for up to 16.5 days after death [30]. Prions, the infectious agents that cause Creutzfeldt-Jakob disease are highly resistant to conventional methods of sterilization and disinfection [31, 32]. Therefore, every cadaver should be regarded as an infectious material, and specific safety precautions should be obtained to avoid accidental disease transmission. These include a detailed file, indicating the reason of death and containing previous hospital records for the deceased, using embalming chemical, although there is inadequate information about their disinfectant properties, discard tissue remnants, debris and the sheet covering the table after the dissection is completed, and clean the environment with a phenolic disinfectant [28].

The challenges, risk of disease transmission and costs associated with the use of cadaveric tissues for biomechanical studies, in addition to inconsistencies between tissue specimens, has prompted the development of synthetic tissues that accurately reproduce the complex properties of natural human tissues. Synthetic tissues provide a number of advantages over cadaveric bone for biomechanical studies. First, the quality of cadaveric bone varies widely, requiring a large number of specimens to be tested for important results. Second, fixation implants are often used in relatively young patients whose bone quality can be poorly represented by the often osteoporotic bone characteristics of the elderly donors. Third, for a long-term in vitro study to be performed, deterioration of the properties of the cadaveric bone over time must be considered. Fourth, the bone density of cadaveric bone is highly variable and has a significant effect on the results of biomechanical testing; bone mineral density tests such as dual X-ray absorptiometry (DXA) are widely available, easy to perform and correlate highly and significantly with bone strength in many modes of failure [33].

Initially introduced in the late 1980s, sawbones (artificial or composite bones) were designed to simulate the bone architecture, as well as the physical properties of bones. Since then, sawbones have been extensively used in orthopaedic biomechanical research and for surgical training that traditionally relied on cadavers [21]. Unlike cadaveric bones, sawbones are relatively inexpensive, widely available, have minimal variability between specimens, are not ethically controversial, and require no special storage or preservation techniques and no Institutional Review Board/Ethics Committee approval. Sawbones are available in various formulations to optimize desirable properties for specific applications, such as enhanced radiopacity or ease of cutting, reaming, or drilling [21, 34, 35].

The basic components of sawbones are plastics and epoxies. First-generation sawbones consisted of a rigid polyurethane foam core surrounded by an epoxy-reinforced, braided glass sleeve. However, mismatch between the glass fiber size and epoxy component resulted in delamination of the cortical material, and were subsequently poorly represented in the biomechanics literature [21, 36]. Second-generation sawbones were fiberglass-fabric-reinforced (FFR) composites, constructed from layers of woven fiberglass matting that were solidified into the cortical matrix by the pressure injection of epoxy resin [37, 38]. However, they had no intramedullary canal and limitations of the FFR cortical material were noted; although the 45° orientation of glass fibers in the FFR matrix excelled at reproducing physiologic lateral bending rigidity, this geometry bolstered material strength in the rotational plane [21, 22, 36]. Third generation sawbones were manufactured with an entirely pressure-injected technique by which short glass fiber reinforced (SGFR) epoxy was injection-molded around the polyurethane foam core to form the cortical wall [36]. Additionally, direct castings of cadaver bones from an adult male donor was undertaken for the third generation sawbones to maintain a high level of anatomic fidelity with regard to topography of the cortical wall and gross specimen size. Including the glass fiber and epoxy resin components in the same material phase improved the consistency in bone shape and anatomic detail within and between specimens [37-39]. The properties of the new SGFR material resulted in better approximation of organic bone when stressed in the rotational plane. However, third-generation sawbones were still stiffer (140%) than cadaveric specimens under torsion, and their physiologic bending properties were similar to second-generation sawbones [36]. Fourth-generation sawbones are currently available. They use the same SGFR construction and injection molding manufacturing process as the third-generation models and therefore have similar reproduction of anatomic detail and consistency of geometry of the cortical wall. However, they benefit from an optimized epoxy

component, resulting in incremental improvement in torsional and bending stiffness [21]. Moreover, the fourth-generation sawbones have a high fatigue threshold, improved thermal and solvent stability, and better bicortical screw purchase relative to third-generation models, making them ideal for repeat loading applications and biomechanical testing under physiologic conditions, which is critical in orthopaedic implant testing [39-41]. However, fourth-generation sawbones have demonstrated uncharacteristic interspecimen variability, and cannot undergo bone remodeling, features seen in bones having undergone previous fixation. Therefore, many investigators still prefer to perform small-scale cadaver validation studies when testing previously unscrutinized composites [21].

The mechanical environment of the tissue, tissue motion and load distribution are also important. In most cases, a clinical outcome relates to adaptation of tissues to their mechanical environment. Potting sawbones may be problematic as living bone is never strongly secured proximally and distally; however, secured potting is necessary for mechanical stability. Tissue load magnitudes and directions are an estimate of stresses and strains, and can be measured with a reasonable accuracy using validated approaches [42-46].

Relevance in Orthopaedic Biomechanics

Researchers rarely show whether differences in tissue material (living or dead) might have relevance to their study question. This is a necessity if adaptation is not considered within the framework of the question being asked [47]. A recent article raised the issue of relevance for biomechanical studies in orthopaedics [47], arguing that biomechanical studies have exerted a relatively minor impact in clinical practice, and that most of biomechanical studies have had limited relevance to biology and clinical medicine because of failure to distinguish living from non-living systems by their biological responsiveness, tissue adaptation and tolerance [47]. When these fundamental requirements are met, biomechanical studies can provide powerful tools to explain the function of the body and to predict the success or failure of treatments prior to using them on patients. If these are not met, any biomechanical study is suspect, and requires to be interpreted with great caution. Yet, no current approach to numerically predicting tissue adaptation has been correlated with clinically relevant situations [47]. Furthermore, biomechanics should not be considered the study of the mechanical aspects of the structure and function of biological systems because biological systems do not have mechanical aspects [2]. Living tissues properties differ from those of non-living tissues. The key distinctions are that living tissue is able to sense the environment, respond to their external environment in a seemingly infinite number of ways, and adapt over time. A living tissue is not static, but through internal processes alters certain of its characteristics in response to external stimuli [48]; some living tissues are able to repair themselves, and modify their behavior in both the short term and the long term [2, 19, 47-49]. Failure to recognize living and non-living tissue may be a major source of scatter in biomechanical studies [19]. In this setting, biomechanical studies using non-living, non-adaptable systems would be questionable; consequently, the use of the term "necromechanics", from the ancient Greek "νεκρός" (dead), as previously suggested, would be logical [47].

A valid study should not contain flaws and should be internally consistent. For biomechanical studies, validity requires a context of adaptation and tissue material clarification that should be explicitly reported. The researcher should recognize and should inform the readers for their study design and limitations [50]. Biomechanical studies should also have clinical relevance, which should be meaningful for the clinicians and their patients [47].

Several key parameters are required for a biomechanical study to be clinically relevant in orthopaedics [47]. The mechanical parameter chosen should be a surrogate for relevant biological behavior; obviously, the choice of the mechanical parameter depends on the question being asked. The mechanical parameter should also be obtained with physiological force magnitudes and directions. Most studies apply a single loading regimen; instead, a set of loading regimens that represent the entire range of repetitive loadings experienced *in vivo* should be used. Load magnitudes should not be chosen for convenience. Tissue type (living or not) and its tolerance to the mechanical parameter should be clarified and discussed in relation to the experiment. Tissue adaptation to the mechanical parameters over time should be addressed for the biomechanical study to be clinically relevant [47]. If the above parameters are not addressed when designing a study or addressing its limitations, the results of that investigation should be regarded with caution. In contrast, if the above requirements are met, the power of the biomechanical studies increases and their results are important and valid for clinical decision making and to predict success or failure of treatments prior to attempting them in patients [47].

Conclusion

Novel research directions should be emphasized in future clinical orthopaedic biomechanical studies for their direct clinical application, with emphasis on scientific integrity and clinical relevance. Readers have to critically and properly interpret the results of biomechanical studies. The authors should clarify the tissue type, tolerance and adaptation should provide key questions that are clinically relevant, and should inform the readers that biomechanical models have inherent limitations. Limitations should not be suppressed but rather discussed in the discussion section of the article; if not, the study results should be regarded with caution.

Competing Interests

The authors have declared that no competing interest exists.

References

1. Knudson D. Fundamentals of biomechanics 2nd edition. Springer Science+Business Media LLC; 2007.
2. Hatze H. The meaning of the term: "Biomechanics". J Biomech. 1974; 7:189-90.
3. Lyons AS, Petrucelli RJ. Medicine: an illustrated history. Harry N. Abrams; 1978: 616.
4. Mow Van C, Huiskes R. A Brief History of Science and Orthopaedic Biomechanics. In: Basic Orthopaedic Biomechanics and Mechano-Biology, 3rd Edition. Lippincott Williams & Wilkins; 2005.
5. Boorstin DJ. The discoverers: a history of man's search to know his world and himself. New York: Vintage Books; 1983; 745.
6. Glenn J. Scientific genius: the twenty greatest minds. New York: Crescent Books; 1996: 160.
7. Borelli GA. De Motu Animalium. Edited, Rome, Ex typographia Angeli Bernabò; 1680.
8. Ascenzi A. Biomechanics and Galileo Galilei. J Biomech. 1993; 26:95-100.
9. Fung YC. Biomechanics. Trans Am Soc Mech Eng. 1966; 204.
10. Fung YC. Biomechanics: its scope, history, and some problems of continuum mechanics in physiology. Appl Mech Rev. 1968; 21(1):1-20.
11. Fung YC. Biomechanics: mechanical properties of living tissues. New York: Springer-Verlag; 1981:433.
12. Pope MH, DeVocht JW. The clinical relevance of biomechanics. Neurol Clin. 1999; 17(1):17-41.
13. Carter H. The New Theatre and Cinema of Soviet Russia, Being an Analysis and Synthesis of the Unified Theatre. Edited, London, Chapman and Dodd, Ltd; 1924.
14. Stedman TL. A Practical Medical Dictionary. Edited, New York, William Wood and Company; 1933.
15. Steindler A. Presidential Address. J Bone Joint Surg Am. 1933; 15:567-73.
16. Atwater AE. Kinesiology/biomechanics: Perspectives and trends. Res Q Exerc Sport. 1980; 51(1):193-218.
17. Wilkerson JD. Biomechanics. In: J. D. Massengale & R. A. Swanson (Eds.), The history of exercise and sport science. Champaign, IL: Human Kinetics; 1997; 321-66.
18. Burton K, Thompson J, Brinckmann P. Clinical biomechanics. Clin Biomech (Bristol, Avon). 1986; 1(1):1.
19. Black J. Dead or alive: the problem of in vitro tissue mechanics. J Biomed Mater Res. 1976; 10:377-89.
20. Heng PA, Cheng CY, Wong TT, et al. Virtual reality techniques. Application to anatomic visualization and orthopaedics training. Clin Orthop Relat Res. 2006; 442:5-12.
21. Elfar J, Menorca RM, Reed JD, et al. Composite bone models in orthopaedic surgery research and education. J Am Acad Orthop Surg. 2014; 22:111-20.
22. Cristofolini L, Viceconti M. Mechanical validation of whole bone composite tibia models. J Biomech. 2000; 33(3):279-88.
23. Kerckaert I, Van Hoof T, Pattyn P et al. Endogent: Centre for Anatomy and Invasive Techniques. Int J Experiment Clin Anat. 2008; 2:28-33.
24. Thiel W. The preservation of the whole corpse with natural color [German]. Ann Anat. 1992; 174(3):185-95.
25. Brand RA. Can Biomechanics Contribute to Clinical Orthopaedic Assessments? The Iowa Orthopaedic Journal. 1989; 9:61-64.
26. Kappel TJ, Reinartz JJ, Schmid JL, Holter JJ, Azar MM. The viability of Mycobacterium tuberculosis in formalin fixed autopsy tissue: Review of literature and brief report. Hum Pathol. 1996; 27:1361-1364.
27. Cattaneo C, Nuttall PA, Molendini LO, Pellegrinelli M, Grandi M, Sokol RJ. Prevalence of HIV and hepatitis C markers among a cadaver population in Milan. J Clin Pathol. 1999; 52:267-270.
28. Demiryürek D, Bayramoğlu A, Ustaçelebi S. Infective agents in fixed human cadavers: a brief review and suggested guidelines. Anat Rec. 2002; 269(4):194-197.
29. Barnett JR, McCauley RL, Schutzler S, Sheridan K, Heggers JP. 2001. Cadaver donor discards secondary to serology. J Burn Care Rehabil. 2001; 22:124-127.
30. Douceron H, Deforges L, Gherardi R, Sobel A, Chariot P. Long-lasting postmortem viability of human immunodeficiency virus: A potential risk in forensic medicine practice. Forensic Sci Int. 1993; 60:61-66.
31. Brown P, Liberski PP, Wolff A, Gajdusek DC. Resistance of scrapie infectivity to steam autoclaving after formaldehyde fixation and limited survival after ashing at 360°C: Practical and theoretical implications. J Infect Dis. 1990; 161:467-472.
32. Brown P, Gajdusek DC. Survival of scrapie after three years internment. Lancet. 1991; 337:269-270.
33. Ambrose CG, Kiebzak GM, Sabonghy EP, Tabor OB, Peindl RD, Clanton TO, Anderson RA, Davis WH. Biomechanical testing of cadaveric specimens: importance of bone mineral density assessment. Foot Ankle Int. 2002; 23(9):850-855.
34. [Internet] Sawbones: Product Catalogue. Pacific Research Laboratories. Vashon, WA. Revised December 6, 2013. http://www.sawbones.com/products/productlist.aspx?111.
35. Reed JD, Stanbury SJ, Menorca RM, et al. The emerging utility of composite bone models in biomechanical studies of the hand and upper extremity. J Hand Surg Am. 2013; 38:583-7.
36. Heiner AD, Brown TD. Structural properties of a new design of composite replicate femurs and tibias. J Biomech. 2001; 34(6):773-81.
37. Heiner AD. Structural properties of fourth-generation composite femurs and tibias. J Biomech. 2008; 41(15):3282-4.
38. [Internet] MatWeb: Material Property Data. Sawbones Second-Generation Simulated Cortical Bone. Revised December 6, 2013. http://www.matweb.com/search/DataSheet.aspx?MatGUID=82d1e15c662d4c97b75df5e9d9171da9&ckck=1.
39. Chong AC, Friis EA, Ballard GP, et al. Fatigue performance of composite analogue femur constructs under high activity loading. Ann Biomed Eng. 2007; 35(7):1196-205.
40. Chong AC, Miller F, Buxton M, et al. Fracture toughness and fatigue crack propagation rate of short fiber reinforced epoxy composites for analogue cortical bone. J Biomech Eng. 2007; 129(4):487-93.
41. Zdero R, Olsen M, Bougherara H, et al. Cancellous bone screw purchase: A comparison of synthetic femurs, human femurs, and finite element analysis. Proc Inst Mech Eng H. 2008; 222(8):1175-83.
42. Franzen H, Mjoberg B, Onnerfalt R. Early migration of acetabular components revised with cement. A roentgen stereophotogrammetric study. Clin Orthop Relat Res. 1993; 287:131-4.
43. Brand RA, Pedersen DR, Davy DT, et al. Comparison of hip force calculations and measurements in the same patient. J Arthroplasty. 1994; 9:45-51.
44. Linder L. Implant stability, histology, RSA and wear—more critical questions are needed. A view point. Acta Orthop Scand. 1994; 65:654-8.
45. Önsten I, Akesson K, Besjakov J, et al. Migration of the Charnley stem in rheumatoid arthritis and osteoarthritis. A roentgenstereophotogrammetric study. J Bone Joint Surg Br. 1995; 77:18-22.
46. Brand RA, Stanford CM, Swan CC. How do tissues respond and adapt to stresses around a prosthesis? A primer on finite element stress analysis for orthopaedic surgeons. Iowa Orthop J. 2003; 23:13-22.
47. Brand RA. Biomechanics or necromechanics? Or how to interpret biomechanical studies. Iowa Orthop J. 2002; 22:110-5.
48. Haapasalo H, Kontulainen S, Sievänen H, et al. Exercise-induced bone gain is due to enlargement in bone size without a change in volumetric bone density: a peripheral quantitative computed tomography study of the upper arms of male tennis players. Bone. 2000; 27(3):351-7.
49. Brand RA. What do tissues and cells know of mechanics? Ann Med. 1997; 29(4):267-9.
50. Oreskes N, Shrader-Frechette K, Belitz K. Verification, validation, and confirmation of numerical models in the earth sciences. Science. 1994; 264:641-6.