Journal of Biomechanics 45 (2012) 625–633

Contents lists available at SciVerse ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Perspective article

Considerations for reporting finite element analysis studies in biomechanics

Ahmet Erdemir [a,b,*], Trent M. Guess [c], Jason Halloran [a,b], Srinivas C. Tadepalli [d], Tina M. Morrison [e]

[a] Computational Biomodeling (CoBi) Core, Lerner Research Institute, Cleveland Clinic, Cleveland, OH 44195, USA
[b] Department of Biomedical Engineering, Lerner Research Institute, Cleveland Clinic, Cleveland, OH 44195, USA
[c] Department of Civil and Mechanical Engineering, University of Missouri – Kansas City, Kansas City, MO 64110, USA
[d] Department of Orthopaedics and Sports Medicine, University of Washington, Seattle, WA 98195, USA
[e] Center for Devices and Radiological Health, Food and Drug Administration, Silver Spring, MD 20933, USA

ARTICLE INFO

Article history:
Accepted 16 November 2011

Keywords:
Standards in modeling
Tissue mechanics
Joint biomechanics
Musculoskeletal system
Device mechanics
Device evaluation

ABSTRACT

Simulation-based medicine and the development of complex computer models of biological structures is becoming ubiquitous for advancing biomedical engineering and clinical research. Finite element analysis (FEA) has been widely used in the last few decades to understand and predict biomechanical phenomena. Modeling and simulation approaches in biomechanics are highly interdisciplinary, involving novice and skilled developers in all areas of biomedical engineering and biology. While recent advances in model development and simulation platforms offer a wide range of tools to investigators, the decision making process during modeling and simulation has become more opaque. Hence, reliability of such models used for medical decision making and for driving multiscale analysis comes into question. Establishing guidelines for model development and dissemination is a daunting task, particularly with the complex and convoluted models used in FEA. Nonetheless, if better reporting can be established, researchers will have a better understanding of a model's value and the potential for reusability through sharing will be bolstered. Thus, the goal of this document is to identify resources and considerate reporting parameters for FEA studies in biomechanics. These entail various levels of reporting parameters for model identification, model structure, simulation structure, verification, validation, and availability. While we recognize that it may not be possible to provide and detail all of the reporting considerations presented, it is possible to establish a level of confidence with selective use of these parameters. More detailed reporting, however, can establish an explicit outline of the decision-making process in simulation-based analysis for enhanced reproducibility, reusability, and sharing.

1. Introduction

Advances in computer model development and simulation software facilitate physics-based explorations relying on the principles of mechanics. Due to the increased capabilities of solvers to accommodate robust and speedy simulations, the availability of algorithms to represent various physiological phenomena, and the development of user interfaces that bring model development to the masses, numerous contributions have been made through the broad use of modeling and simulation in medicine and clinical translational research by a diverse group of investigators. The downside, however, is that the modeler's decision-making process and the solution approach have become less transparent. Moreover, modelers are sometimes uninformed about the limitations of their model and the simulation software, causing the readers, users, and reviewers of such models to be uninformed. Standards for model and data sharing (International Organization for Standardization, 2000, 2006; CFD General Notation System, v2.0.20) and a variety of guides and standards for verification and validation (American Society of Mechanical Engineers, 2006, 2009) try to establish confidence in modeling and simulation results for the readers, users, and reviewers. However, while these existing standards are helpful, they do not explicitly address the issue of reporting and communication, particularly regarding finite element analysis (FEA) in the field of medicine and biomechanics, where complex models of non-linear mechanics of biological structures are developed.

FEA was developed over 70 years ago to solve complex elasticity and structural analysis problems in civil and aeronautical engineering (Zienkiewicz, 2004). Applications of FEA were expanded to simulations in biomechanics, as portrayed by investigations utilizing this computational tool for more than three decades, dating back to the late 1970s (Miller, 1979). For example, the potential of FEA to address problems in orthopedic biomechanics (Huiskes and

* Correspondence author at: Lerner Research Institute, Cleveland Clinic, Department of Biomedical Engineering (ND20), Computational Biomodeling Core, 9500 Euclid Avenue, Cleveland, OH 44195, USA. Tel.: +1 216 445 9523; fax: +1 216 444 9198
E-mail address: erdemira@ccf.org (A. Erdemir).

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doi:10.1016/j.jbiomech.2011.11.038

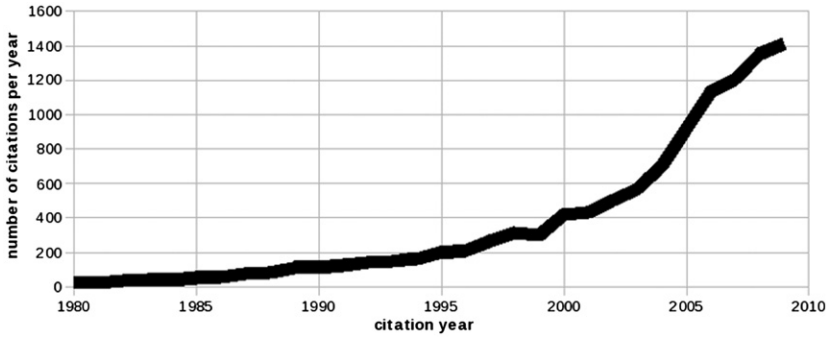

Fig. 1. Published studies utilizing finite element analysis as a research tool (from 1980 to 2009). Search conducted on Pubmed (http://www.pubmed.org) with the search string "finite element". As of July 7, 2010, 839 articles published in year 2010 included this keyword (not shown in figure). Total number of citations before 1980 is 22. Image courtesy of Ahmet Erdemir, Department of Biomedical Engineering, Cleveland Clinic.

Chao, 1983) and ventricular systems (Yin, 1985) has been demonstrated. Currently, studies incorporating FEA to support basic and clinical translational research in medicine exceed ten thousand (as of July 7, 2010, the cumulative total number of citations for the search string "finite element" is 11,300; searched in PubMed, http://www.pubmed.org). Of these, more than 250 are review articles and more than 50 articles focus on multiscale analysis. In addition, the number of studies using FEA appears to be increasing geometrically (Fig. 1).

With the increasing number of FEA studies, FEA practice in biomechanics continues to pose a challenge for model development, sharing and reporting. In FEA, model definitions and development procedures are tightly coupled to the simulation method and the solver capabilities. FEA software (commercial or otherwise) commonly relies on embedded mathematical models of physical phenomena, e.g., solid mechanics. Some packages are specifically designed for the analysis of biological structures, e.g., Continuity 6 for cardiac mechanics (http://www.continuity.ucsd.edu/Continuity) and FEBio for biomechanical applications (http://mrl.sci.utah.edu/software/febio), but many are presented as general analysis tools.

In many cases, decisions made during model development depend on the specific solver capabilities. Furthermore, while many simulation software packages exist, a universally accepted unified model definition language, i.e., mark-up language, does not exist. Current model related data exchange standards (International Organization for Standardization, 2006) may not readily be applicable to complex biomechanical FEA models. Therefore, a practical solution is needed to enhance current model development and dissemination efforts. One possible solution is to establish reporting parameters of FEA models and simulation studies. Although it may not be practical to immediately realize the long term goal of adopting standards for model exchangeability, immediately augmenting model reporting across disciplines could facilitate transition to higher level modeling standards. Because most FEA share common features during model development and simulation process, it is possible to compile parameters for reporting items that may be important for model reproducibility and may help the scientific community to assess the overall quality, scientific rigor, and utility of the model. Thus, the purpose of this document is not to present "how-to-run FEA studies" or "best practices in FEA" but to present easy to follow, adaptive, and expandable reporting parameters for modeling and simulation studies in biomechanics with an emphasis on FEA. The document is targeted for scientists and engineers (in academia, industry, government, etc.) for the purpose of disseminating biomechanical models, publishing, and evaluating others' simulation research; for journal editors and reviewers judging manuscript quality; for agencies and grant reviewers during crucial decision making; and for professionals (in biomedical and clinical translational research) to promote good modeling and simulation practice. This lengthy document is not a substitute for author or reviewer expertise. However, it can highlight the important aspects of the modeling and simulation process, particularly in multi-disciplinary research where the necessary expertise may not be readily available.

Throughout this document, the term "model" refers to the computational representation of the biological structure and its components, e.g., cartilage between knee joints or vessel wall with stent, for FEA, including discretized geometric representation, constitutive relationships of substructures, interactions between substructures, and loading and boundary conditions representative of the biomechanical environment. The term "simulation" refers to the solution process of the finite element representation of the biological structure and its components through the use of finite element analysis techniques. Finally, the term "multiscale" conveys the interactions between higher spatial scales of the Physiome, between joint/organ biomechanics and tissue mechanics, and between tissue mechanics and cell biomechanics (Tawhai et al., 2009).

2. Reporting parameters

Initiatives and guidelines for reporting research methods and findings have been listed by the National Library of Medicine, National Institutes of Health (http://www.nlm.nih.gov/services/research_report_guide.html). This list includes many standards that address a wide range of applications. These standards are undoubtedly valuable for the reporting process and result in valid (consistent, reproducible and accountable) studies to their respective fields. For example, the Consolidated Standards of Reporting Trials (CONSORT) provides a well established 25-item checklist for reporting of randomized clinical trials (Moher et al., 2010; Schulz et al., 2010). Within that list, computational studies addressing biological processes have generally adopted the Minimum Information of Biological and Biomedical Investigations (MIBBI) (Taylor et al., 2008). Within MIBBI, the Minimum Information About a Simulation Experiment (MIASE) specifically addresses the minimum necessary information to recreate general computational simulations. While the general guidelines provided by MIASE may be applicable to FEA studies, specific and detailed recommendations are missing for adequate reporting of this complex analysis tool in biomechanical investigations.

For reporting on FEA, a few general guidelines have been recommended. Clinical Biomechanics specifies that simulations need to comply with the requirements listed in a useful editorial by Viceconti et al. (2005). However, it stops short of developing