

See discussions, stats, and author profiles for this publication at: <https://www.researchgate.net/publication/331836367>

Finite Element Analysis for Biomedical Engineering Applications

Book · March 2019

DOI: 10.1201/9780429061264

CITATIONS

14

READS

5,764

1 author:



Zhaochun Yang

23 PUBLICATIONS 430 CITATIONS

SEE PROFILE

Finite Element Analysis for Biomedical Engineering Applications



Taylor & Francis

Taylor & Francis Group

<http://taylorandfrancis.com>

Finite Element Analysis for Biomedical Engineering Applications

Z. Yang



CRC Press

Taylor & Francis Group

Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business

CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

© 2019 by Taylor & Francis Group, LLC
CRC Press is an imprint of Taylor & Francis Group, an Informa business

No claim to original U.S. Government works

Printed on acid-free paper

International Standard Book Number-13: 978-0-367-18218-2 (Hardback)

This book contains information obtained from authentic and highly regarded sources. Reasonable efforts have been made to publish reliable data and information, but the author and publisher cannot assume responsibility for the validity of all materials or the consequences of their use. The authors and publishers have attempted to trace the copyright holders of all material reproduced in this publication and apologize to copyright holders if permission to publish in this form has not been obtained. If any copyright material has not been acknowledged please write and let us know so we may rectify in any future reprint.

Except as permitted under U.S. Copyright Law, no part of this book may be reprinted, reproduced, transmitted, or utilized in any form by any electronic, mechanical, or other means, now known or hereafter invented, including photocopying, microfilming, and recording, or in any information storage or retrieval system, without written permission from the publishers.

For permission to photocopy or use material electronically from this work, please access www.copyright.com (<http://www.copyright.com/>) or contact the Copyright Clearance Center, Inc. (CCC), 222 Rosewood Drive, Danvers, MA 01923, 978-750-8400. CCC is a not-for-profit organization that provides licenses and registration for a variety of users. For organizations that have been granted a photocopy license by the CCC, a separate system of payment has been arranged.

Trademark Notice: Product or corporate names may be trademarks or registered trademarks, and are used only for identification and explanation without intent to infringe.

Visit the Taylor & Francis Web site at
<http://www.taylorandfrancis.com>

and the CRC Press Web site at
<http://www.crcpress.com>

Contents

Preface	xiii
About the Author.....	xv

Chapter 1	Introduction	1
------------------	---------------------------	----------

PART I Bone

Chapter 2	Bone Structure and Material Properties	5
2.1	Bone Structure	5
2.2	Material Properties of Bone	7
	References	8

Chapter 3	Simulation of Nonhomogeneous Bone.....	9
3.1	Building Bone Model from CT Data.....	9
3.1.1	CT Data.....	10
3.1.2	Finite Element Model	10
3.1.3	Calculation of the Average CT Number (<i>HU</i>) ...	10
3.1.4	Material Property Assignment	13
3.1.5	Discussion.....	14
3.1.6	Summary.....	14
3.2	Interpolation of Bone Material Properties	15
3.2.1	Multidimensional Interpolation	15
3.2.1.1	RBAS Algorithm	15
3.2.1.2	NNEI Algorithm	15
3.2.1.3	LMUL Algorithm	16
3.2.2	Interpolation of Material Properties of the Ankle.....	16
3.2.2.1	Defining Material Properties of Bone Using the RBAS Algorithm.....	18
3.2.2.2	Defining Material Properties of Bone Using the NNEI Algorithm	18
3.2.2.3	Defining Material Properties of Bone Using the LMUL Algorithm	18
3.2.2.4	Defining Material Properties of Bone Using a Mixed Method	19
3.2.3	Discussion.....	20
3.2.4	Summary.....	21
	References	21

Chapter 4	Simulation of Anisotropic Bone	23
4.1	Anisotropic Material Models	23
4.2	Finite Element Model of Femur with Anisotropic Materials	25
4.2.1	Finite Element Model of Femur with Anisotropic Materials	25
4.2.2	Simulation of Mechanical Testing of the Femur ..	29
4.2.3	Discussion.....	29
4.2.4	Summary.....	31
	References	31
 Chapter 5	 Simulation of Crack Growth Using the eXtended Finite Element Method (XFEM).....	 33
5.1	Introduction to XFEM	33
5.1.1	Singularity-Based Method	33
5.1.2	Phantom-Node Method.....	34
5.1.3	General Process for Performing XFEM Crack-Growth Simulation	35
5.2	Simulation of Crack Growth of the Cortical Bone	35
5.2.1	Finite Element Model	37
5.2.1.1	Geometry and Mesh.....	37
5.2.1.2	Material Properties	37
5.2.1.3	Definition of Crack Front.....	38
5.2.1.4	Local Coordinate Systems	38
5.2.1.5	Loading and Boundary Conditions	39
5.2.1.6	Solution Setting.....	39
5.2.2	Results	40
5.2.3	Discussion.....	41
5.2.4	Summary.....	41
	References	42

PART II Soft Tissues

Chapter 6	Structure and Material Properties of Soft Tissues	45
6.1	Cartilage	45
6.1.1	Structure of Cartilage	45
6.1.2	Material Properties of Cartilage.....	45
6.2	Ligaments	46
6.2.1	Structure of Ligaments	46
6.2.2	Material Properties of Ligaments	46
6.3	Intervertebral Disc	47
	References	48

Chapter 7 Nonlinear Behavior of Soft Tissues..... 49

7.1 Hyperelastic Models 49

7.2 Finite Element Analysis of the Abdominal Aortic Aneurysm Wall..... 51

 7.2.1 Finite Element Model 52

 7.2.1.1 Geometry and Mesh..... 52

 7.2.1.2 Material Model 53

 7.2.1.3 Loading and Boundary Conditions 55

 7.2.1.4 Solution Setting..... 56

 7.2.2 Results 56

 7.2.3 Discussion..... 57

 7.2.4 Summary..... 58

 References 58

Chapter 8 Viscoelasticity of Soft Tissues 61

8.1 The Maxwell Model 61

8.2 Study of PDL Creep 63

 8.2.1 Finite Element Model 63

 8.2.1.1 Geometry and Mesh..... 63

 8.2.1.2 Material Models 64

 8.2.1.3 Boundary Conditions..... 64

 8.2.1.4 Loading Steps..... 65

 8.2.2 Results 65

 8.2.3 Discussion..... 65

 8.2.4 Summary..... 67

 References 67

Chapter 9 Fiber Enhancement 69

9.1 Standard Fiber Enhancement 69

 9.1.1 Introduction of Standard Fiber Enhancement 69

 9.1.2 IVD Model with Fiber Enhancement..... 69

 9.1.2.1 Finite Element Model of IVD..... 70

 9.1.2.2 Results 73

 9.1.2.3 Discussion..... 73

 9.1.2.4 Summary 75

9.2 Mesh-Independent Fiber Enhancement..... 75

 9.2.1 Introduction of Mesh-Independent Fiber Enhancement 75

 9.2.2 IVD Model with Mesh-Independent Fiber Enhancement 76

 9.2.2.1 Finite Element Model 76

	9.2.2.2	Creating the Fibers.....	76	
	9.2.2.3	Results	78	
	9.2.2.4	Summary	79	
9.3	Material Models Including Fiber Enhancement.....		79	
9.3.1	Anisotropic Material Model with Fiber Enhancement		79	
9.3.2	Simulation of Anterior Cruciate Ligament (ACL)		84	
	9.3.2.1	Finite Element Model	85	
	9.3.2.2	Results	88	
	9.3.2.3	Discussion.....	88	
	9.3.2.4	Summary	88	
	References.....		90	
Chapter 10				
	USERMAT for Simulation of Soft Tissues		93	
10.1	Introduction of Subroutine UserHyper		93	
10.2	Simulation of AAA Using UserHyper		93	
	10.2.1	Using Subroutine UserHyper to Simulate Soft Tissues of the Artery	93	
	10.2.2	Validation	95	
	10.2.3	Study the AAA Using UserHyper	96	
	10.2.4	Discussion	96	
	10.2.5	Summary.....	98	
	References.....		99	
Chapter 11				
	Modeling Soft Tissues as Porous Media		101	
11.1	CPT Elements		101	
11.2	Study of Head Impact.....		102	
	11.2.1	Finite Element Model of the Head	102	
		11.2.1.1	Geometry and Mesh	102
		11.2.1.2	Material Properties.....	102
		11.2.1.3	Loading and Boundary Conditions.....	102
	11.2.2	Results	105	
	11.2.3	Discussion	108	
	11.2.4	Summary.....	108	
11.3	Simulation of Creep Behavior of the IVD.....		108	
	11.3.1	Finite Element Method.....	108	
		11.3.1.1	Geometry and Mesh	108
		11.3.1.2	Material Properties.....	108
		11.3.1.3	Loading and Boundary Conditions.....	109
		11.3.1.4	Solution Setting.....	109

11.3.2	Results	110
11.3.3	Discussion	111
11.3.4	Summary.....	113
References	.....	113

PART III *Joints*

Chapter 12	Structure and Function of Joints.....	117
	Reference	118

Chapter 13	Modeling Contact	119
13.1	Contact Models	119
13.2	3D Knee Contact Model	120
13.2.1	Finite Element Model.....	120
13.2.1.1	Geometry and Mesh	120
13.2.1.2	Material Properties.....	123
13.2.1.3	Contact Pairs	123
13.2.1.4	Boundary Conditions.....	127
13.2.2	Results.....	128
13.2.3	Discussion	129
13.2.4	Summary.....	130
13.3	2D Poroelastic Model of Knee	130
13.3.1	Finite Element Model.....	131
13.3.1.1	Geometry and Mesh	131
13.3.1.2	Material Properties.....	133
13.3.1.3	Contact Definitions	134
13.3.1.4	Boundary Conditions and Loading	134
13.3.1.5	Solution Setting.....	136
13.3.2	Results.....	136
13.3.3	Discussion	137
13.3.4	Summary.....	138
References	.....	140

Chapter 14	Application of the Discrete Element Method for Study of the Knee Joint.....	141
14.1	Introduction of Discrete Element Method	141
14.2	Finite Element Model.....	141
14.2.1	Line-Plane Intersection.....	142
14.2.2	Building Springs.....	143
14.2.3	Boundary Conditions	145

14.2.4	Results	145
14.2.5	Discussion	146
14.2.6	Summary	147
References	.....	147

PART IV Simulation of Implants

Chapter 15	Study of Contact in Ankle Replacement	151
15.1	Finite Element Model	151
15.1.1	Geometry and Mesh	151
15.1.2	Material Properties	151
15.1.3	Contact Definition	153
15.1.4	Loading and Boundary Conditions	153
15.2	Results	154
15.3	Discussion	155
15.4	Summary	156
References	.....	156
 Chapter 16	 Simulation of Shape Memory Alloy (SMA)	
	Cardiovascular Stent	157
16.1	SMA Models	157
16.1.1	SMA Model for Superelasticity	157
16.1.2	SMA Model with Shape Memory Effort	160
16.2	Simulation of Angioplasty with Vascular Stenting	161
16.2.1	Finite Element Model	162
16.2.1.1	Geometry and Mesh	162
16.2.1.2	Material Properties	163
16.2.1.3	Contact Pairs	164
16.2.1.4	Solution Setting	165
16.2.2	Results	166
16.2.3	Discussion	166
16.2.4	Summary	167
References	.....	167
 Chapter 17	 Wear Model of Liner in Hip Replacement	 169
17.1	Wear Simulation	169
17.1.1	Archard Wear Model	169
17.1.2	Improving Mesh Quality during Wear	169
17.2	Simulating Wear of Liner in Hip Replacement	170
17.2.1	Finite Element Method	170
17.2.1.1	Geometry and Mesh	170

	17.2.1.2	Material Properties.....	170
	17.2.1.3	Wear Model.....	171
	17.2.1.4	Contact Definition	172
	17.2.1.5	Loading and Boundary Conditions.....	172
	17.2.1.6	Solution Setting.....	172
	17.2.2	Results.....	173
	17.2.3	Discussion	173
	17.2.4	Summary.....	175
	References		175
Chapter 18	Fatigue Analysis of a Mini Dental Implant (MDI).....		177
18.1	SMART Crack-Growth Technology		177
18.2	Study of Fatigue Life of an MDI		178
18.2.1	Finite Element Model.....		179
18.2.1.1	Geometry and Mesh		179
18.2.1.2	Material Properties.....		179
18.2.1.3	Loading and Boundary Conditions.....		180
18.2.1.4	Setting up Fracture Calculation		180
18.2.2	Results.....		181
18.2.3	Discussion		183
18.2.4	Summary.....		184
	References		184
 PART V <i>Retrospective</i>			
Chapter 19	Retrospective		187
19.1	Principles for Modeling Biology		187
19.2	Meshing Sensitivity.....		188
19.3	Units.....		188
19.4	Workbench.....		188
19.5	ANSYS Versions.....		188
Appendix 1:	Input File of the Multidimensional Interpolation in Section 3.2.2.....		189
Appendix 2:	Input File of the Anisotropic Femur Model in Section 4.2		203
Appendix 3:	Input File of the XFEM Crack-Growth Model in Section 5.2.....		207

Appendix 4: Input File of the Abdominal Aortic Aneurysm Model
in Section 7.2 213

Appendix 5: Input File of the Periodontal Ligament Creep Model
in Section 8.2 217

Appendix 6: Input File of the Intervertebral Disc Model with Fiber
Enhancement in Section 9.1.2 221

Appendix 7: Input File of the Intervertebral Disc Model with Mesh
Independent Fiber Enhancement in Section 9.2.2 229

Appendix 8: Input File of the Anterior Cruciate Ligament Model
in Section 9.3.2 235

Appendix 9: Input File of Subroutine UserHyper in Section 10.2 239

Appendix 10: Input File of the Head Impact Model in Section 11.2 243

Appendix 11: Input File of the Intervertebral Disc Model in Section 11.3 245

Appendix 12: Input File of the Knee Contact Model in Section 13.2 249

Appendix 13: Input File of the 2D Axisymmetrical Poroelastic Knee
Model in Section 13.3 259

Appendix 14: Input File of the Discrete Element Model of Knee Joint
in Chapter 14 265

Appendix 15: Input File of the Material Definition of the Cancellous Bone
in Chapter 15 273

Appendix 16: Input File of the Stent Implantation Model in Chapter 16 281

Appendix 17: Input File of the Wear Model of Hip Replacement
in Chapter 17 289

Appendix 18: Input File of the Mini Dental Implant Crack-Growth Model
in Chapter 18 293

Index 299

Preface

In 2001, I came to the University of Pittsburgh to pursue my PhD. As I learned about biomechanics, I became fascinated by the complications of biology. In the past 17 years, I had been working on many bioengineering projects with professors from the University of Pittsburgh, University of Pennsylvania, Allegheny General Hospital, and Soochow University. My long-time research has given me experience in finite element modeling in the field of biomedical studies. I have chosen to record my experiences in a book which, I hope, will encourage medical researchers to do further investigations. Yet, even after 17 years of study and research, I recognize that I still have more to learn about biomechanics. Should this book, therefore, contain errors, I ask readers to point them out to me so that I can address and correct them.

While I wrote this book, I received help and encouragement from many of my friends, including Frank Marx, Dr. J.S. Lin, Dr. Richard Debski, and Fayan Xu. Dr. Zhi-Hong Mao reviewed the whole manuscript. I am grateful for his constructive comments that have greatly improved the quality of the book. I give a special thanks to Ronna Edelstein for her time and effort in revising my manuscript. I express my great appreciation to the staff at CRC Press, especially Marc Gutierrez and Kari Budyk for their assistance in publishing the book. Finally, I thank my family, especially my wife, Peng, and my two children, for their constant support.



Taylor & Francis

Taylor & Francis Group

<http://taylorandfrancis.com>

About the Author

Z. Yang earned a PhD in mechanical engineering at the University of Pittsburgh in 2004. Over the last 17 years, he has collaborated with professors from various colleges, such as the University of Pennsylvania and University of Pittsburgh, and finished a number of biomedical projects. Currently, he is a senior software engineer in the field of finite element analysis with over 10 years' experience.



Taylor & Francis

Taylor & Francis Group

<http://taylorandfrancis.com>

1 Introduction

Because people are living longer in today's world, more individuals are dealing with a variety of diseases. Some common diseases are associated with the mechanical states of human organs. For example, hips often break when older people fall, and the lumbar disc degenerates due to excessive loadings over the long term. An abdominal aortic aneurysm (AAA) occurs when the stresses of the AAA wall exceed the strength of the wall tissue. Treatment of these diseases requires an understanding of the stress-states of relevant parts under various conditions. When some parts of the human body degenerate and lose their function, people may have to undergo implant surgeries, such as stent implantation for treatment of atherosclerosis and total knee replacement to regain the walking function. Although these implants can improve the person's quality of life significantly, they can also raise other issues, such as medial tilting in ankle replacements and fatigue and wear of the liner in hip implants. To solve these issues and improve the medical designs, it is vital to study the mechanical behavior of the implants.

While researchers are testing the mechanical responses of the organs and the implants in the lab, they also emphasize numerical simulations, especially finite element analysis. Since the 1970s, some well-known commercial finite element codes, such as ANSYS, NASTRAN, MARC, ABAQUS, LSDYNA, and COMSOL, have been developed to solve the structural problems. Among them, ANSYS software has the most powerful nonlinear solver, and hence it has become the most widely used software in both academia and industry. Over the past decade, many advanced finite element technologies have been developed in ANSYS. The purpose of this book is to simulate some common medical problems using finite element advanced technologies, which paves a path for medical researchers to perform further studies.

The book consists of four main parts. Each part begins by presenting the structure and function of the biology, and then it introduces the corresponding ANSYS advanced features. The final discussion highlights some specific biomedical problems simulated by ANSYS advanced features.

The topic of Part I is bone. After this introductory chapter, Chapter 2 introduces the structure and material properties of bone. Chapter 3 discusses the nonhomogeneous character of bone, including modeling it by computed tomography (CT) in Section 3.1 and by multidimensional interpolation in Section 3.2. Chapter 4 describes how to build a finite element model of anisotropic bone, and the crack-growth in the micro-structure of cortical bone is simulated by eXtended Finite Element Model (XFEM) in Chapter 5.

Part II, which deals with soft tissues, is very detailed. Chapter 6 introduces the structure and material properties of soft tissues like cartilage, ligament, and intervertebral discs (IVDs). Next, Chapter 7 presents the nonlinear behavior of soft tissues and simulation of AAA in ANSYS190. Chapter 8 examines the viscoelasticity of soft tissues, including its application to the study of periodontal ligament creep.

Some soft tissues are enhanced by fibers. Chapter 9 discusses three approaches of fiber enhancement in ANSYS190: (1) standard mesh-dependent fiber enhancement, in which the fibers are created within the regular base mesh; (2) mesh-independent fiber enhancement that creates fibers independent of the base mesh; and (3) the anisotropic material model with fiber enhancement. The first two approaches are utilized to simulate the fibers in the annulus of the intervertebral disc (IVD).

Many nonlinear material models in ANSYS are available for the simulation of soft tissues. If the experimental data of one biological material do not fit any of these models, the researchers may turn to USERMAT in ANSYS. Chapter 10 focuses on the topic of how to develop user material models in ANSYS.

The soft tissues are biphasic, consisting of 30%–70% water. Chapter 11 introduces ways of modeling soft tissues as porous media and the application of biphasic modeling in head impact and IVD creep research.

Part III describes joint simulation. After briefly introducing the structure of joints in Chapter 12, in the next chapter, Section 13.1 defines three contact types in a whole-knee simulation, and a two-dimensional (2D) axisymmetrical poroelastic knee model is built in Section 13.2. Then, the discrete element method of knee joint that is implemented in ANSYS is analyzed in Chapter 14.

Part IV presents a number of implant simulations. Chapter 15 studies the contact of the talar component and the bone to investigate medial tilting in ankle replacement. The stent implantation is simulated in Chapter 16 using the shape memory alloy super-elasticity model. The Archard wear model is applied to study the wear of the hip implant in Chapter 17. Chapter 18 predicts the fatigue life of a mini-dental implant using ANSYS SMART technology.

Chapter 19 presents a retrospective look at the entire content of the book. Some guidelines are summarized for the simulation of biomedical problems.

The biomedical problems in this book have been simulated using ANSYS Parametric Design Language (APDL). Reading this book requires knowledge of APDL. To learn APDL, I suggest first reading the ANSYS help documentation and then practice some technical demonstration problems available in this documentation. All APDL input files of the finite element models in the book are provided in the appendixes.

REFERENCES

1. Gray, H., *Anatomy of the Human Body*. Lea & Febiger, Philadelphia, 1918.
2. Pal, S., *Design of Artificial Human Joints & Organs*. Springer, 2014.
3. Fung, Y. C., *Biomechanics: Mechanical Properties of Living Tissues*. 2nd ed., Springer, New York, 1993.
1. Taddei, F., Pancanti, A., and Viceconti, M., “An improved method for the automatic mapping of computed tomography numbers onto finite element models.” *Medical Engineering & Physics*, Vol. 26, 2004, pp. 61–69.
2. Kalender, W. A., “A phantom for standardization and quality control in spinal bone mineral measurements by QCT and DXA: Design considerations and specifications.” *Medical Physics*, Vol. 19, 1992, pp. 583–586.
3. Carter, D. R., and Hayes, W.C., “The compressive behaviour of bone as a two-phase porous structure.” *Journal of Bone and Joint Surgery, American Volume*, Vol. 59, 1977, pp. 954–962.

4. Wirtz, D. C., Schiffers, D., Pandorf, T., Radermacher, K., Weichert, D., and Forst, R., "Critical evaluation of known bone material properties to realize anisotropic FE simulation of the proximal femur." *Journal of Biomechanics*, Vol. 33, 2000, pp. 1325–1330.
5. Amidror, I., "Scattered data interpolation methods for electronic imaging systems: A survey." *Journal of Electronic Imaging*, Vol. 11, 2002, pp. 157–176.
6. ANSYS19.0 Help Documentation in the help page of product ANSYS190.
7. Jensen, N. C., Hvid, I., and Krøner, K., "Strength pattern of cancellous bone at the ankle joint." *Engineering in Medicine*, Vol. 17, 1988, pp. 71–76.
1. Wirtz, D. C., Schiffers, N., Pandorf, T., Radermacher, K., Weichert, D., and Forst, R., "Critical evaluation of known bone material properties to realize anisotropic FE-simulation of the proximal femur." *Journal of Biomechanics*, Vol. 33, 2000, pp. 1325–1330.
2. García, E. G., *Double Experimental Procedure for Model-Specific Finite Element Analysis of the Human Femur and Trabecular Bone*, Technische Universität München, 2013.
1. ANSYS 19.0 Help Documentation in the help page of product ANSYS190.
2. Mohsin, S., O'Brien, F. J., and Lee, T. C., "Osteonal crack barriers in ovine compact bone." *Journal of Anatomy*, Vol. 208, 2006, pp. 81–89.
3. Vashishth, D., Tanner, K. E., and Bonfield, W., "Contribution, development and morphology of microcracking in cortical bone during crack propagation." *Journal of Biomechanics*, Vol. 33, 2000, pp. 1169–1174.
4. Najafi, A. R. et al., "Haversian cortical bone model with many radial microcracks: An elastic analytic solution." *Medical Engineering & Physics*, Vol. 29, 2007, pp. 708–717.
5. Najafi, A. R. et al., "A fiber-ceramic matrix composite material model for osteonal cortical bone fracture micromechanics: Solution of arbitrary microcracks interaction." *Journal of the Mechanical Behavior of Biomedical Materials*, Vol. 2, 2009, pp. 217–223.
6. Huang, J., Rapoff, A. J., and Haftka, R. T., "Attracting cracks for arrestment in bone-like composites." *Materials and Design*, Vol. 27, 2006, pp. 461–469.
7. Vergani, L., Colombo, C., and Libonati, F., "Crack propagation in cortical bone: A numerical study." *Procedia Materials Science*, Vol. 3, 2014, pp. 1524–1529.
8. Baptista, R., Almeida, A., and Infante, V., "Micro-crack propagation on a biomimetic bone like composite material studied with the extended finite element method." *Procedia Structural Integrity*, Vol. 1, 2016, pp. 18–25.
1. Jun, H., Evans, T. M., and Mente, P. L., "Study on the damage mechanism of articular cartilage based on the fluid-solid coupled particle model." *Advances in Mechanical Engineering*, Vol. 7, 2015.
2. Guilak, F., "The slippery slope of arthritis." *Arthritis Rheumatology*, Vol. 52, 2005, pp. 1632–1633.
3. Kastelic, J., Palley, I., and Baer, E., "The multicomposite ultrastructure of tendon." *Connective Tissue Research*, Vol. 6, 1978, pp. 11–23.
4. Fung, Y. C., *Biomechanics: Mechanical Properties of Living Tissues*. 2nd ed., Springer, New York, 1993.
5. Pal, S., *Design of Artificial Human Joints & Organs*. Springer, New York, 2014.
6. Koopman, W. J. and Moreland, L. W., *Arthritis and Allied Conditions*. 15th ed., Lippincott Williams & Wilkins, Philadelphia, 2005.
1. ANSYS19.0 Help Documentation in the help page of product ANSYS190.
2. Patel, M. I., Hardman, D. T. A., Fisher, C. M., and Appleberg, M., "Current views on the pathogenesis of abdominal aortic aneurysms." *Journal of the American College of Surgeons*, Vol. 181, 1985, pp. 371–382.
3. Di Martino, E. S., Bohra, A., Vande Geest, J. P., Gupta, N., Makaroun, M., and Vorp, D. A., "Biomechanical properties of ruptured versus electively repaired

- abdominal aortic aneurysm wall tissue.” *Journal of Vascular Surgery*, Vol. 43, 2006, pp. 570–576.
4. Raghavan, M., Kratzberg, J., and da Silva, E. S., “Heterogeneous, variable wall-thickness modeling of a ruptured abdominal aortic aneurysm.” *Proceedings of the 2004 International Mechanical Engineering Congress and R&D Expo IMECE2004*, 2004.
 5. Raghavan, M. L., Vorp, D. A., Federle, M. P., Makaroun, M. S., and Webster, M. W., “Wall stress distribution on three-dimensionally reconstructed models of human abdominal aortic aneurysm.” *Journal of Vascular Surgery*, Vol. 31, 2000, pp. 760–769.
 6. Vorp, D. A., Raghavan, M. L., and Webster, M. W., “Mechanical wall stress in abdominal aortic aneurysm: Influence of diameter and asymmetry.” *Journal of Vascular Surgery*, Vol. 27, 1998, pp. 632–639.
 7. Wilson, K. A., Lee, A. J., Hoskins, P. R., Fowkes, F. G. R., Ruckley, C. V., and Bradbury, A. W., “The relationship between aortic wall distensibility and rupture of infrarenal abdominal aortic aneurysm.” *Journal of Vascular Surgery*, Vol. 37, 2003, pp. 112–117.
 8. Raghavan, M. L., Kratzberg, J., Castro de Tolosa, E. M., Hanaoka, M. M., Walker, P., and da Silva, E. S., “Regional distribution of wall thickness and failure properties of human abdominal aortic aneurysm.” *Journal of Biomechanics*, Vol. 39, 2006, pp. 3010–3016.
 9. Scotti, C. M., Jimenez, J., Muluk, S. C., and Finol, E. A., “Wall stress and flow dynamics in abdominal aortic aneurysms: Finite element analysis vs. fluid-structure interaction.” *Computer Methods in Biomechanics and Biomedical Engineering*, Vol. 11, 2008, pp. 301–322.
 10. Scotti, C. M., Shkolnik, A. D., Muluk, S., and Finol, E. A., “Fluid–structure interaction in abdominal aortic aneurysms: Effects of asymmetry and wall thickness.” *Biomedical Engineering Online*, Vol. 5, 2005, pp. 64.
 11. Raut, S., Chandra, S., Shum, J., Washington, C. B., Muluk, S. C., Finol, E. A., and Rodriguez, J. F., “Biological, geometric, and biomechanical factors influencing abdominal aortic aneurysm rupture risk: A comprehensive review.” *Recent Patents on Medical Imaging*, Vol. 3, 2013, pp. 44–59.
 12. de Ruiz, G. S., Antón, R. S., Cazón, A., Larraona, G. S., and Finol, E. A., “Anisotropic abdominal aortic aneurysm replicas with biaxial material characterization.” *Medical Engineering & Physics*, Vol. 38, 2016, pp. 1505–1512.
 13. de Ruiz, G. S., Cazón, A., Antón, R., and Finol, E. A., “The relationship between surface curvature and abdominal aortic aneurysm wall stress.” *Journal of Biomechanical Engineering*, Vol. 139, 2017, doi: 10.1115/1.4036826
 14. Raghavan, M. L., Webster, M. W., and Vorp, D. A., “Ex-vivo biomechanical behavior of abdominal aortic aneurysm: Assessment using a new mathematical model.” *Annals of Biomedical Engineering*, Vol. 24, 1996, pp. 573–582.
 1. ANSYS190 Help Documentation in the help page of product ANSYS190.
 2. Motoyoshi, M., Hirabayashi, M., Shimazaki, T., and Namura, S., “An experimental study on mandibular expansion: Increases in arch width and perimeter.” *European Journal of Orthodontics*, Vol. 24, 2002, pp. 125–130.
 3. Katona, T. R. and Qian, H., “A mechanism of noncontinuous supraosseous tooth eruption.” *American Journal of Orthodontics & Dentofacial Orthopedics*, Vol. 120, 2001, pp. 263–271.
 4. Tanne, K., “Stress induced in the periodontal tissue at the initial phase of the application of various types of orthodontic forces: 3-dimensional analysis using a finite element method.” *Osaka Daigaku Shigaku Zasshi*, Vol. 28, 1983, pp. 209–261.
 5. Ross, G. G., Lear, C. S., and Decos, R., “Modeling the lateral movements of teeth.” *Journal of Biomechanics*, Vol. 9, 1976, pp. 723–734.

6. McCormack, S. W., Witzel, U., Watson, P. J., Fagan, M. J., and Gröning, F., “The biomechanical function of periodontal ligament fibres in orthodontic tooth movement.” *PLOS One*, Vol. 9, 2014, p. e102387.
7. Su, M. Z., Chang, H. H., Chiang, Y. C., Cheng, J. H., Fuh, L. J., Wang, C. Y., and Lin, C. P., “Modeling viscoelastic behavior of periodontal ligament with nonlinear finite element analysis.” *Journal of Dental Sciences*, Vol. 8, 2013, pp. 121–128.
8. Yang, Y. and Tang, W., “Analysis of mechanical properties at different levels of the periodontal ligament.” *Biomedical Research*, Vol. 28, 2017, pp. 8958–8965.
1. ANSYS19.0 Help Documentation in the help page of product ANSYS190.
2. Paremer, A., Fumer, S., and Rice, D. P., *Musculoskeletal Conditions in the United States*. American Academy of Orthopaedic Surgeons, Park Ridge, IL, 1992.
3. Eberline, R., Holzapfel, G. A., and Schulze-Bauer, C. A., “An anisotropic constitutive model for annulus tissue and enhanced finite element analyses of intact lumbar disc bodies.” *Computer Methods in Biomechanics and Biomedical Engineering*, Vol. 4, 2001, pp. 209–230.
4. Jones, A. C., and Wilcox, R. K., “Finite element analysis of the spine: Towards a framework of verification, validation, and sensitivity analysis.” *Medical Engineering & Physics*, Vol. 30, 2008, pp. 1287–1304.
5. Lin, H., Pan, Y., Liu, C., Huang, L., Huang, C., and Chen, C., “Biomechanical comparison of the K-ROD and Dynesys dynamic spinal fixator systems—a finite element analysis.” *Bio-Medical Materials and Engineering*, Vol. 23, 2013, pp. 495–505.
6. Little, J., and Adam, C., “Geometric sensitivity of patient-specific finite element models of the spine to variability in user selected anatomical landmarks.” *Computer Methods in Biomechanics and Biomedical Engineering*, Vol. 18, 2013, pp. 676–688.
7. Xu, M., Yang, J., Lieberman, J. H., and Haddas, R., “Lumbar spine finite element model for healthy subjects: Development and validation.” *Computer Methods in Biomechanics and Biomedical Engineering*, Vol. 20, 2017, pp. 1–15.
8. Elliott, D. M., and Setton, L. A., “A linear material model for fiber-induced anisotropy of the annulus fibrosus.” *Journal of Biomedical Engineering*, Vol. 122, 2000, pp. 173–179.
9. Wagner, D. R., and Lotz, J. C., “Theoretical model and experimental results for the non-linear elastic behavior of human annulus fibrosus.” *Journal of Orthopaedic Research*, Vol. 22, 2006, pp. 901–909.
10. Fujita, Y., Duncan, N. A., and Lotz, J. C., “Radial tensile properties of the lumbar annulus fibrosus are site and degeneration dependent.” *Journal of Orthopaedic Research*, Vol. 15, 1997, pp. 814–819.
11. Fetto, J. E., and Marshall, J. L., “The natural history and diagnosis of anterior cruciate ligament insufficiency.” *Clinical Orthopaedics*, Vol. 147, 1980, pp. 29–38.
12. Johnson, R. J., “The anterior cruciate: A dilemma in sports medicine.” *International Journal of Sports Medicine*, Vol. 3, 1982, pp. 71–79.
13. Zantop, T., Petersen, W., and Fu, F. H., “Anatomy of the anterior cruciate ligament.” *Operative Techniques in Orthopaedics*, Vol. 15, 2005, pp. 20–28.
14. Daniel, W. J. T., “Three-dimensional orthotropic viscoelastic finite element model of a human ligament.” *Computer Methods in Biomechanics and Biomedical Engineering*, Vol. 4, 2001, pp. 265–279.
15. Hirokawa, S., and Tsuruno, R., “Three-dimensional deformation and stress distribution in an analytical/computational model of the anterior cruciate ligament.” *Journal of Biomechanics*, Vol. 33, 2000, pp. 1069–1077.
16. Pioletti, D. P., Rakotomanana, L. R., Benvenuti, J. F., and Leyvraz, P. F., “Viscoelastic constitutive law in large deformations: Application to human knee ligaments and tendons.” *Journal of Biomechanics*, Vol. 31, 1998, pp. 753–757.

17. Limbert, G., and Taylor, M., "Three-dimensional finite element modelling of the human anterior cruciate ligament. Influence of the initial stress field." *Computer Methods in Biomechanics and Biomedical Engineering*, Vol. 3, 2001, pp. 355–360.
18. Vairis, A., Petousis, M., Vidakis, N., Stefanoudakis, G., and Kandyla, B., "Finite element modelling of a novel anterior cruciate ligament repairing device." *Journal of Engineering Science and Technology Review*, Vol. 6, 2013, pp. 1–6.
19. Parekh, J. N., *Using Finite Element Methods to Study Anterior Cruciate Ligament Injuries: Understanding the Role of ACL Modulus and Tibial Surface Geometry on ACL Loading*, University of Michigan, 2013.
20. Open Knee(s): Virtual Biomechanical Representations of the Knee Joint. Website: simtk.org/projects/openknee.
21. Peña, E., Calvo, B., Martínez, M. A., and Doblaré, M., "An anisotropic visco-hyperelastic model for ligaments at finite strains. Formulation and computational aspects." *International Journal of Solids and Structures*, Vol. 44, 2007, pp. 760–778.
1. ANSYS19.0 Help Documentation in the help page of product ANSYS190.
2. Wulandana, R., and Robertson, A. M., "An inelastic multi-mechanism constitutive equation for cerebral arterial tissue." *Biomechanics and Modeling in Mechanobiology*, 4, 2005, 235–248.
3. Sidorov, S. *Finite Element Modelling of Human Artery Tissue with a Nonlinear Multi-Mechanism Inelastic Material*. University of Pittsburgh, 2007.
1. ANSYS19.0 Help Documentation in the help page of product ANSYS190.
2. Vermeer, P. A., and Verrujit, A., "An accuracy condition for consolidation by finite elements." *International Journal for Numerical and Analytical Methods in Geomechanics*, Vol. 5, 1981, pp. 1–14.
3. Bruns, J. J., and Hauser, W. A., "The epidemiology of traumatic brain injury: A review." *Epilepsia*, Vol. 44, 2003, pp. 2–10.
4. Chan, H. S., "Mathematical model for closed head impact." *18th Stapp Car Crash Conference of the Society of Automotive Engineers*, Ann Arbor, MI, 1974, pp. 557–579.
5. Ward, C., "Finite element models of the head and their use in brain injury research." *26th Stapp Car Crash Conference of the Society of Automotive Engineers*, Ann Arbor, MI, 1982, pp. 71–85.
6. Hosey, R. R., and Liu, Y. K., "A homeomorphic finite element model of the human head and neck." *Finite Elements in Biomechanics*, 1982, pp. 379–401.
7. Ruan, J. S., Khalil, T., and King, A. I., "Dynamic response of the human head to impact by three-dimensional finite element analysis." *Journal of Biomechanical Engineering*, Vol. 116, 1994, pp. 44–51.
8. Chen, H. X., *Finite Element Investigation of Closed Head Injuries*. University of Manitoba, 2010.
9. Wang, C. Z., *Finite Element Modeling of Blast-Induced Traumatic Brain Injury*. University of Pittsburgh, 2013.
10. Suh, J. K., and Bai, S., "Finite element formulation of biphasic poroviscoelastic model for articular cartilage." *Journal of Biomechanical Engineering*, Vol. 120, 1998, pp. 195–201.
11. Suh, J. K., and DiSilvestro, M. R., "Biphasic poroviscoelastic behavior of hydrated biological soft tissue." *Journal of Applied Mechanics*, Vol. 66, 1999, pp. 528–535.
12. Levenston, M. E., Frank, E. H., and Grodzinsky, A. J., "Variationally derived 3-field finite element formulations for quasi-static poroelastic analysis of hydrated biological tissues." *Computer Methods in Applied Mechanics and Engineering*, Vol. 156, 1998, pp. 231–246.
13. Paremer, A., Fumer, S., and Rice, D. P., *Musculoskeletal Conditions in the United States*. American Academy of Orthopaedic Surgeons, Park Ridge, IL, 1992.

14. Gilbertson, L. G. et al., "Finite element methods in spine biomechanics research." *Critical Reviews in Biomedical Engineering*, Vol. 23, 1995, pp. 411–473.
15. Massey, C. J., *Finite Element Analysis and Materials Characterization of Changes Due to Aging and Degeneration of the Human Intervertebral Disc*. Drexel University, 2009.
16. Yang, Z. C., *Poroviscoelastic Dynamic Finite Element Model of Biological Tissue*. University of Pittsburgh, 2004.
1. Wooley, P. H., Grimm, M. J., and Radin, E. L., "The structure and function of joints." *Arthritis & Allied Conditions*, 15th edition, Lippincott Williams & Wilkins, Philadelphia, 2005, pp. 151–152.
1. ANSYS 190 Help Documentation in the help page of product ANSYS190.
2. Arden, N., and Nevitt, M. C., "Osteoarthritis: Epidemiology." *Best Practice & Research Clinical Rheumatology*, Vol. 20, 2006, pp. 3–25.
3. Murphy, L., Schwartz, T. A., Helmick, C. G., Renner, J. B., Tudor, G., Koch, G., and Jordan, J. M., "Lifetime risk of symptomatic knee osteoarthritis." *Arthritis & Rheumatism*, Vol. 59, 2008, pp. 1207–1213.
4. Andriacchi, T. P., Mündermann, A., Smith, R. L., Alexander, E. J., Dyrby, C. O., and Koo, S., "A framework for the *in vivo* pathomechanics of osteoarthritis at the knee." *Annals of Biomedical Engineering*, Vol. 32, 2004, pp. 447–457.
5. Taylor, Z. A., and Miller, K., "Constitutive modeling of cartilaginous tissues: A review." *Journal of Applied Biomechanics*, Vol. 22, 2006, pp. 212–229.
6. Peña, E., Del Palomar, A. P., Calvo, B., Martínez, M., and Doblaré, M., "Computational modelling of diarthrodial joints. Physiological, pathological, and post-surgery simulations." *Archives of Computational Methods in Engineering*, Vol. 14, 2007, pp. 47–91.
7. Kazemi, M., Dabiri, Y., and Li, L. P., "Recent advances in computational mechanics of the human knee joint." *Computational and Mathematical Methods in Medicine*, 2013, pp. 1–27.
8. Mononen, M. E., Tanska, P., Isaksson, H., and Korhonen, R. K., "A novel method to simulate the progression of collagen degeneration of cartilage in the knee: Data from the osteoarthritis initiative." *Scientific Reports*, Vol. 6, 2016, pp. 214–215.
9. Open Knee(s): Virtual Biomechanical Representations of the Knee Joint. Website: simtk.org/projects/openknee.
10. Kumar, V. A. and Jayanthi, A. K., "Finite element analysis of normal tibiofemoral joint and knee osteoarthritis: A comparison study validated through geometrical measurements." *Indian Journal of Science and Technology*, Vol. 9, 2016.
11. Mow, V. C., Kuei, S. C., Lai, W. M., and Armstrong, C. G., "Biphasic creep and stress relaxation of articular cartilage in compression, theory and experiments." *Journal of Biomechanical Engineering*, Vol. 102, 1980, pp. 73–84.
12. Chern, K. Y., Zhu, W. B., Kelly, M. A., and Mow, V. C., "Anisotropic shear properties of bovine meniscus." *Transaction of the 36th Annual Meeting of the Orthopaedic Research Society*, New Orleans, 1990, pp. 246.
13. Proctor, C., Schmidt, M. B., Whipple, R. R., Kelly, M. A., and Mow, V. C., "Material properties of the normal medial bovine meniscus." *Journal of Orthopaedic Research*, Vol. 7, 1989, pp. 771–782.
14. Whipple, R. R., Wirth, C. R., and Mow, V. C., "Anisotropic and zonal variations in the tensile properties of the meniscus." *Transaction of the 31st Annual Meeting of the Orthopaedic Research Society*, Las Vegas, 1985, p. 367.
15. Cohen, B., Gardner, T. R., and Ateshian, G. A., "The influence of transverse isotropy on cartilage indentation behavior-A study of the human humeral head." *Transaction of Annual Meeting of 39th Orthopaedic Research Society*, Chicago, 1993, p. 185.

16. Reilly, D. T., and Burstein, A. H., "The mechanical properties of cortical bone." *Journal of Bone & Joint Surgery*, Vol. 56, 1974, pp. 1001–1022.
17. Guo, H. Q., Maher, S. A., and Spilker, R. L., "Biphasic finite element contact analysis of the knee joint using an augmented Lagrangian method." *Medical Engineering & Physics*, Vol. 35, 2013, pp. 1313–1320.
1. Li, G., Sakamoto, M., and Chao, E. Y., "A comparison of different methods in predicting static pressure distribution in articulating joints." *Journal of Biomechanics*, Vol. 30, 1997, pp. 635–638.
2. An, K. N., Himeno, S., Tsumura, H., Kawai, T., and Chao, E. Y., "Pressure distribution on articular surfaces: Application to joint stability evaluation." *Journal of Biomechanics*, Vol. 23, 1990, pp. 1013–1020.
3. Yoshida, H., Faust, A., Wilckens, J., Kitagawa, M., Fetto, J., and Chao, E. Y., "Three-dimensional dynamic hip contact area and pressure distribution during activities of daily living." *Journal of Biomechanics*, Vol. 39, 2006, pp. 1996–2004.
4. Genda, E., Iwasaki, N., Li, G., MacWilliams, B. A., Barrance, P. J., and Chao, E. Y., "Normal hip joint contact pressure distribution in single-leg standing—Effect of gender and anatomic parameters." *Journal of Biomechanics*, Vol. 34, 2001, pp. 895–905.
5. Abraham, C. L., Maas, S. A., Weiss, J. A., Ellis, B. J., Peters, C. L., and Anderson, A. E., "A new discrete element analysis method for predicting hip joint contact stresses." *Journal of Biomechanics*, Vol. 46, 2013, pp. 1121–1127.
6. Kern, A. M., and Anderson, D. D., "Expedited patient-specific assessment of contact stress exposure in the ankle joint following definitive articular fracture reduction." *Journal of Biomechanics*, Vol. 48, 2015, pp. 3427–3432.
7. Anderson, D. D., Iyer, K. S., Segal, N. A., Lynch, J. A., and Brown, T. D., "Implementation of discrete element analysis for subject-specific, population-wide investigations of habitual contact stress exposure." *Journal of Applied Biomechanics*, Vol. 26, 2010, pp. 215–223.
8. Segal, N. A., Anderson, D. D., Iyer, K. S., Baker, J., Torner, J. C., Lynch, J. A., and Brown, T. D., "Baseline articular contact stress levels predict incident symptomatic knee osteoarthritis development in the MOST cohort." *Journal of Orthopaedic Research*, Vol. 27, 2009, pp. 1562–1568.
9. Halloran, J. P., Easley, S. K., Petrella, A. J., and Rullkoetter, P. J., "Comparison of deformable and elastic foundation finite element simulations for predicting knee replacement mechanics." *Journal of Biomechanical Engineering*, Vol. 127, 2005, pp. 813–818.
10. Elias, J. J., and Saranathan, A., "Discrete element analysis for characterizing the patellofemoral pressure distribution: Model evaluation." *Journal of Biomechanical Engineering*, Vol. 135, 2013, pp. 81011.
11. Elias, J. J., Wilson, D. R., Adamson, R., and Cosgarea, A. J., "Evaluation of a computational model used to predict the patellofemoral contact pressure distribution." *Journal of Biomechanics*, Vol. 37, 2004, pp. 295–81302.
12. Smith, C. R., Won Choi, K., Negrut, D., and Thelen, D. G., "Efficient computation of cartilage contact pressures within dynamic simulations of movement." *Computer Methods in Biomechanics and Biomedical Engineering: Imaging & Visualization*, Vol. 1, 2016, pp. 1–8.
13. Foley, J., Dam, A. V., Feiner, S., and Hughes, J., "Clipping Lines," *Computer Graphics*. 3rd ed, Addison–Wesley, Boston, 2013.
1. Gougoulas, N. E., Khanna, A., and Maffulli, N., "History and evolution of total ankle arthroplasty." *British Medical Bulletin*, Vol. 89, 2009, pp. 111–151.
2. Hintermann, B., Total ankle arthroplasty: Historical overview, current concepts and future perspectives. Springer, Austria, 2005.

3. Cui, Y., Hu, P., Wei, N., Cheng, X., Chang, W., and Chen, W., "Finite element study of implant subsidence and medial tilt in agility ankle replacement." *Medical Scientific Monitor*, Vol. 24, 2018, pp. 1124–1131.
4. Miller, M. C., Smolinski, P., Conti, S., and Galik K., "Stresses in polyethylene liners in a semiconstrained ankle prosthesis." *Journal of Biomechanical Engineering*, Vol. 126, 2004, pp. 636–640.
5. Rho, J. Y., Kuhn-Spearing, L., and Zioupos, P., "Mechanical properties and the hierarchical structure of bone." *Medical Engineering & Physics*, Vol. 20, 1998, pp. 92–102.
6. Jensen, N. C., Hvid, I., and Krøner, K., "Strength pattern of cancellous bone at the ankle joint." *Engineering in Medicine*, Vol. 17, 1988, pp. 71–76.
7. Kopperdahl, D. L., and Keaveny, T. M., "Yield strain behavior of trabecular bone." *Journal of Biomechanics*, Vol. 31, 1998, pp. 601–608.
8. Stauffer, R. N., Chao, E. Y. S., and Brewster, R. C., "Force and motion analysis of the normal, diseased, and prosthetic ankle joint." *Clinical Orthopaedics and Related Research*, Vol. 127, 1977, pp. 189–196.
1. Auricchio, F., Taylor, R. L., and Lubliner, J., "Shape-memory alloys: Macromodeling and numerical simulations of the superelastic behavior." *Computational Methods in Applied Mechanical Engineering*, Vol. 146, 1997, pp. 281–312.
2. Souza, A. C., Mamiya, E. N., and Zouain, N., "Three-dimensional model for solids undergoing stress-induced phase transformations." *European Journal of Mechanics-A/Solids*, Vol. 17, 1998, pp. 789–806.
3. Auricchio, F., and Petrini, L., "Improvements and algorithmical considerations on a recent three-dimensional model describing stress-induced solid phase transformations." *International Journal for Numerical Methods in Engineering*, Vol. 55, 2005, pp. 1255–1284.
4. Auricchio, F., Fugazza, D., and DesRoches, R., "Numerical and experimental evaluation of the damping properties of shape-memory alloys." *Journal of Engineering Materials and Technology*, Vol. 128, 2006, pp. 312–319.
5. Auricchio, F., Conti, M., Morganti, S., and Reali, A., "Shape memory alloy: From constitutive modeling to finite element analysis of stent deployment." *CMES*, Vol. 57, 2010, pp. 225–243.
6. Lloyd-Jones, D. et al., "Heart disease and stroke statistics—2009 update: A report from the American Heart Association Statistics Committee and Stroke Statistics Subcommittee." *Circulation*, Vol. 119, 2009, pp. 1–161.
7. Hoffmann, R. et al., "Patterns and mechanisms of in-stent restenosis. A serial intravascular ultrasound study." *Circulation*, Vol. 94, 1996, pp. 1247–1254.
8. Lally, C., Dolan, F., and Pendergrast, P.J., "Cardiovascular stent design and vessel stresses: A finite element analysis." *Journal of Biomechanics*, Vol. 38, 2005, pp. 1574–1581.
1. ANSYS19.0 Help documentation in the help page of product ANSYS190.
2. American Academy of Orthopaedic Surgeons, *Total Hip Replacement*. Accessed on December 3, 2012, from <http://orthoinfo.aaos.org/topic.cfm?topic=a00377>
3. Liu, F., Leslie, I., Williams, S., Fisher, J., and Jin, Z., "Development of computational wear simulation of metal-on-metal hip resurfacing replacements." *Journal of Biomechanics*, Vol. 41, 2008, pp. 686–694.
4. Meng, H. C., and Ludema, K., "Wear models and predictive equations: Their form and content." *Wear*, Vol. 181–183, 1995, pp. 443–457.
5. Archard, J. F., "Contact and rubbing of flat surfaces." *Journal of Applied Physics*, Vol. 24, 1953, pp. 981–988.
6. Ronda, J., and Wojnarowski, P., "Analysis of wear of polyethylene hip joint cup related to its positioning in patient's body." *Acta of Bioengineering and Biomechanics*, Vol. 15, 2013, pp. 77–86.

1. ANSYS 19.0 Help Documentation in the help page of product ANSYS190.
2. Meijer, H. J., Starmans, F. J., Bosman, F., and Steen, W. H., "A comparison of three finite element models of an edentulous mandible provided with implants." *Journal of Oral Rehabilitation*, Vol. 20, 1993, pp. 147–157.
3. Zarb, G. A., and Schmitt, A., "Osseointegration for elderly patients: The Toronto study." *Journal of Prosthetic Dentistry*, Vol. 72, 1994, pp. 559–568.
4. Shatkin, T. E., Shatkin, S., Oppenheimer, B. D., and Oppenheimer, A. J., "Mini dental implants for long-term fixed and removable prosthetics: A retrospective analysis of 2514 implants placed over a five-year period." *Compendium of Continuing Education in Dentistry*, Vol. 28, 2007, pp. 36–43.
5. Gibney, J. W., "Minimally invasive implant surgery." *Journal of Oral Implantology*, Vol. 27, 2001, pp. 73–76.
6. Grbović, A. M., Rašuo, B. P., Vidanović, N. D., and Perić, M. M., "Simulation of crack propagation in titanium mini dental implants (MDI)." *FME Transactions*, Vol. 39, 2011, pp. 165–170.
7. Takayama, Y., Yamada, T., Araki, O., Seki, T., and Kawasaki, T., "The dynamic behavior of a lower complete during unilateral loads: Analysis using the finite element method." *Journal of Oral Rehabilitation*, Vol. 28, 2001, pp. 1064–1074.