A literature survey on the real-time computational simulation of biological organs

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Abstract

This paper lists some references that could in some way be relevant in the context of the real-time computational simulation of biological organs, the research area being defined in a very broad sense. This paper contains 198 references.

Introduction

The present collection of references together with very brief explanations is relevant in the context of answering questions like: "Is it possible to achieve realistic and real-time simulation of biological organs using mesh reduction techniques ('mesh reduction techniques' includes meshfree methods and the boundary element method)? What is the performance (speed and accuracy) of mesh reduction techniques in the context of the realistic and real-time simulation of biological organs? Are mesh reduction techniques viable (and desirable) for the real-time simulation of biological organs? List some references on various meshfree methods? List some books related to these topics? List some theses on these topics? List some references that report the development of surgical simulators? A few important references on allied areas like haptics, virtual reality, parallel computing, neural networks, soft computing, programming, mechanics, numerical techniques, computational techniques, (coupled) particle systems, spring-mass systems, finite element method, boundary element method etc.? References on surgery planning and surgery simulation? References on realistic and/or real-time simulations? References on the computer simulation of biological organs (especially soft biological organs)? A few references on constitutive modeling and parameter estimation? References on some topics which may be of interest to someone involved in research and development activities related to the theme that is broadly described by the above questions?”

The areas which are not surveyed

Literature on approaches like “running simulation in hardware”, embedded systems, building and using custom hardware, custom-built processors, DSP, neurocomputers, Finite Element Embedded Neural Networks (FENN), analogue computers, real-time operating systems, custom operating systems with in-built simulation software etc. has not been given importance. New techniques which are not yet mature or practical like quantum computing, DNA computing etc. are also not looked into. Of course, there are few (if any) references available on the use of these technologies in the context of the simulation of biological organs (or allied research areas).

Even highly regarded review papers may sometimes fail to mention any reference on a topic which is directly relevant to the review topic but which is not known to the academic community which the author of the concerned review paper belongs to. For example, a review paper that aims to exhibit the literature on the computational simulation of biological organs may mention several papers that use the finite element method for the simulations, but the same review-paper may fail to mention even a single paper that uses neural networks for the purpose of the computational simulation of biological organs. It is possible that the present literature survey might also suffer from this problem.

Review papers concentrate on the already existing literature on the chosen topic. They could sometimes also attempt to make predictions on the future research trends, presumably based on an analysis of the existing literature and the present research trends. Of course, predictions could go wrong also, and the future research trends could also be totally different than expected. For example, it may not be 100% impossible for someone to build an analogue computer that could be of very much help to achieve the real-time computational simulation of biological organs. And in the future, it may not be impossible that a quantum computer would be used for the purpose of the real-time computational simulation of biological organs; it may be possible in the future to simulate molecular dynamics simulations in real-time, and it may be possible in the future that a single readily-available processor would contain

1000 cores, which in turn may enable one to achieve very realistic computational simulations of biological organs in real-time. It might be important to note that, as far as the computer simulations (or computational simulations) are concerned, developments in hardware, software, and numerical (or computational) techniques could be interdependent, which could make the prediction of future research trends even more difficult. This limitation with the review papers may apply to the present paper also. Of course, this limitation(?) with the review papers could make the papers less useful to the readers especially in this internet era when one can search for the relevant literature just by typing some keywords (assuming that the proper keywords are known). But of course, a review paper that can give good insights into the probable future research trends could be of help to researchers (especially beginners) who wish to work in the concerned research area.

Literature survey

This author collected about 400 references related to the questions raised in a previous section titled "Introduction". Out of these references, about 200 references are hand-picked, and the present section gives very short notes on each of the references.

Theses

[Alex Rhomberg, 2001] is a doctoral thesis which deals with real-time finite elements (in this thesis, real-time performance is achieved using a parallel computer).

[Andrew Crossan, 2003] is a Ph.D. thesis dealing with the design and evaluation of a haptic veterinary palpation training simulator.

[Jesper Mosegaard, 2004] is a thesis that deals with realtime surgical simulation within the domain of congenital heart diseases.

[Anderson Maciel, 2005] is a Ph.D. thesis that deals with a biomechanics-based articulation model for medical applications.

[Jochen Lang, 2001] develops a robotic system for recording the deformation of an object that is subjected to external forces and for coming up with a model of the deformation from the recorded deformation.

[Han-Wen Nienhuys, 2003] is a thesis dealing with cutting of deformable objects.

[Teeranoot Chanthasopeephan, 2006] is a Ph.D. thesis experimentally obtains the force-displacement data during the cutting of a pig liver, and characterizes the soft tissue, with the intention of achieving the realistic and realtime haptic simulation of the soft tissue.

[Andrew Havens Gosline, 2003] is a thesis dealing with the simulation of linear elastic media with fluid inclusions.

[Brent Michael Dingle, 2007] presents a particle based method of modeling objects and forces for computer animation.

[David Love Tonnesen, 1998] presents a technique based on dynamically coupled particle systems. The technique can represent objects that can dynamically change (e.g., fluids), and pairwise potential energy functions are often used in this technique to calculate forces between the particles. The reference shows that the technique is a useful alternative to traditional techniques in these areas: free form shape modeling, computer assisted animation, surface reconstruction. The reference also notes that when the technique is used for computer assisted animation, the technique can quite reliably model the physical behaviour of flexible solids and fluids.

[Amy Elizabeth Kerdok, 2006] develops a realistic and physically-based constitutive model for a pig liver. Finite deformations (~30% nominal strain) are considered. The thesis identifies the material parameters of the constitutive model also.

[Martin Kauer, 2001] deals with the characterization of soft tissues through the inverse finite element method and aspiration experiments. A pig kidney (for ex-vivo experiments) and human uteri (for in-vivo and ex-vivo experiments) are the organs considered. Hyperelasticity and quasi-linear viscoelasticity are assumed.

[Zhaochun Yang, 2004] develops a poroviscoelastic dynamic finite element model that can describe biological tissues.

Books

[Grewal B. S., 1996] is a book on engineering mathematics.

[Rudra Pratap, 2010] is an introduction to MATLAB. [Smith I. M., 1995] is a book on Fortran 90. [Alastair McKinstry, Alin Elena, Ruairi Nestor] is a just eleven page introduction to Fortran, but it covers most of the commonly used features of the language. [Blaise Barney] provides a working knowledge of the Message Passing Interface (MPI).

[Ibrahim Zeid, Sivasubramanian R., 2007] is a book on CAD/CAM.

[Srinath L. S., 2003] is a book on solid mechanics.

[Warren C. Young, Richard G. Budynas, 2002] gives formulae for stress and strain. [Lingaiah K., 1984], [Mahadevan K., Balaveera Reddy K., 2000] are the handbooks and contain data useful for mechanical design, including formulae for stress, strain, deflection etc.

[Allan F. Bower, 2009] gives a very practical explanation of solid mechanics, continuum mechanics, and the Finite Element Method.

[Lawrence E. Malvern, 1969], [Truesdell C., Noll W., 2004], [Antonio Romano, Renato Lancellotta, Addolorata Marasco, 2006] are some of the books on continuum mechanics.

[Irving H. Shames, Clive L. Dym, 1991], [Singiresu S. Rao, 2005], [Chandrakant S. Desai, John F. Abel, 1987] are a few books on the Finite Element Method. [Reddy J. N., 2004] is an introduction to nonlinear finite element analysis. [Zhangxin Chen, 2005] is a quite rigorous treatment of the Finite Element Method. [Philippe G. Ciarlet, 1978] fully analyzes the mathematical foundations of the finite element method. [Gilbert Strang, George J. Fix, 2008] demonstrates the mathematical foundations of the finite element method, but the book is readable for non-mathematicians. [Thomas J. R. Hughes, 2000] is a book which provides quite mathematical treatment of the finite element method, but the book can be understood by non-mathematicians still. Fully understanding the mathematical basis of the finite element method requires a knowledge of functional analysis, and some of the books that deal functional analysis are [Lebedev L. P., Vorovich I. I., 2003], [Bryan P. Rynne, Martin A. Youngson, 2008]. [Kung-Ching Chang, 2005] may also be of help while studying the mathematical basis of nonlinear analysis. [Cornelius Lanczos, 1986] is an informal but scholarly exposition of analytical mechanics with coverage of basic concepts, calculus of variations, principle of virtual work etc.

[Carlos Felippa, 1998] has very good course material that deals with different aspects and applications of the Finite Element Method. The course material is quite exhaustive.

[Ang W. T., 2007], [Gernot Beer, Ian Moffat Smith, Christian Duenser, 2008], [Brebbia C. A., 1978], [Brebbia C. A., Dominguez J.] are some of the books that deal with the Boundary Element Method. [Alok Sutradhar, Glaucio H. Paulino, Leonard J. Gray, 2008] deals with Symmetric Galerkin Boundary Element Method which is one of the many types of the Boundary Element Method.

[Youssef F. Rashed] is a beautiful tutorial on the Boundary Element Method.

[Liu G. R., Gu Y. T., 2005], [Shaofan Li, Wing Kam Liu, 2007], [Youping Chen, James D. Lee, Azim Eskandarian, 2006] are some of the books on Meshfree Methods (also called Meshless Methods).

[Fung Y. C., 2004] deals with the mechanical properties of different tissues. It provides mechanical models that represent the behavior of different tissues, and based on experimental results, it provides the values of different constants in these models also.

Relevant literature

[Mandayam A. Srinivasan, et al.] is a progress report from the Laboratory for Human and Machine Haptics, which reports the ongoing work in the lab. It touches upon such topics like biomechanics of touch (e.g., measurement of spatial pressure distribution on the human skin during tactile sensing of objects, video-microscopic investigation of primate fingertip mechanics, frequency response of human skin in vivo to mechanical stimulation, finite element models of the primate fingertip), sensorimotor psychophysics (e.g., tactile perception threshold measurements), haptic device development (e.g., tactile perception test apparatus), human computer interactions (e.g., collaborative haptics), medical applications (e.g., in vivo characterization of the mechanical behavior of soft tissues for surgical simulation, tool-tissue collision prediction, meshless simulation techniques, graphical rendering with point-based models, multi-rate rendering, role of fidelity of multimodal simulation in virtual reality based surgical training).

[M. Chen, C. Correa, S. Islam, M. W. Jones, P. Y. Shen, D. Silver, S. J. Walton, P. J. Willis, 2005] is a state of the art report surveying different techniques available for manipulating, deforming and animating discretely sampled object representations (DSORs).

[Jia-Quan Wang, Yan-Jun Zeng, X-Y Li] assesses the role of the four major operational variables in the radial keratotomy operation (RK) which is performed to correct myopic eyes. The reference also studies the deformation of the cornea after the operation and it attempts to provide some valuable references for clinical practice. The finite element method is used during simulations.

[Y. Ng, C. Song, D. McLean, S. M. Shimi, T. G. Frank, A. Cuschieri, 2003] develops a suture analogue that is suitable for surgery that uses staple constructed from NiTi shape memory alloy (SMA). The staple is closed by resistive heating via a pulse of electrical current. High-resolution thermal imaging is used to observe the dynamic temperature distributions in SMA staples as a function of the pulse parameters. The data obtained can be used to validate computational finite-element models of the heat transport phenomena. Heat sink effect of the electrical contact rails as well as the presence of contact hotspots are considered so that deployment protocols are optimized and thermal collateral damage to tissue is minimized.

[M.N. Godo, K.T. Morgan., R.B. Richardson, J.S. Kimbell, 1995] deals with the reconstruction of complex passageways for simulations of transport phenomena and the development of a graphical user interface for biological applications.

[Pradeep Ramuhalli, Lalita Udpa, Satish S. Udpa, 2005] proposes a finite-element neural network (FENN) obtained by embedding a finite-element model in a neural network architecture; this enables fast and accurate solution of differential equations (both forward and inverse problems). The source cites a few references that deal with the topic of merging numerical methods with neural networks.

[Karol Miller, Kiyoyuki Chinzei, Girma Orssengo, Piotr Bednarz, 2000] reports the in-vivo mechanical properties of brain tissue. The reference uses a hyper-viscoelastic constitutive model to obtain the material parameters from experimental results.

[Stefan Zachow, Michael Zilske, Hans-Christian Hege, 2007] deals with 3D reconstruction of individual anatomy from medical image data. It focuses on segmentation and geometry processing in particular.

[X Li, R J Cripps, 2007] presents an algorithm for finding all k-nearest neighbours in three-dimensional scattered points, and the application of the algorithm in reverse engineering.

[Yi Liu, Amy E. Kerdok, Robert D. Howe, 2004] applies a nonlinear hyperelastic 8-chain network constitutive law to model soft tissues undergoing large indentations. Also, a finite element model of soft tissue indentation is developed and validated using the constitutive law. The work could serve as an initial method for determining the unique material parameters of breast tissue from indentation experiments.

[M. Hauth, J. Gross, W. Straber, G.F. Buess, 2003] deals with soft tissue simulation that is based on measured data. It presents a finite element system based on a sophisticated material model which is better suited for dynamical computations when compared to the standard approaches. A hierarchical basis and a stabilized Runge-Kutta method are used to achieve fast and accurate simulations.

[William E. Lorensen, Harvey E. Cline, 1987] presents an algorithm for 3D surface construction, which is known as the "Marching Cubes" algorithm.

[S. De, J.-W. Hong, K. J. Bathe, 2003] reports the new developments and new applications of the method of finite spheres. In particular, it uses the method of finite spheres in a surgical simulator; the commercial finite element program 'ADINA' is also used in the work.

[Suvranu De, Jung Kim, Yi-Je Lim, Mandayam A. Srinivasan, 2005] uses the point collocation-based method of finite spheres (PCMFS) for real time simulation of soft tissues during minimally invasive surgery (MIS). The reference also discusses the integration of the methodologies into a practical surgical simulation system.

[Suleiman M. BaniHani, Suvranu De, 2009] makes a comparison of some model order reduction methods for fast simulation of soft tissue response while using the point collocation-based method of finite spheres.

[Maud Marchal, Emmanuel Promayon, Jocelyne Troccaz, 2005] presents a new approach for soft tissue modelling which integrates the interactions between a given soft organ and its surrounding organs. The proposed model is applied to the simulation of the prostate-bladder set. The model is compared to the finite element method in order to quantify its performance and physical realism.

[Han-Wen Nienhuys, A. Frank van der Stappen, 2001] combines the Finite Element (FE) method and interactive cutting without requiring expensive matrix updates or precomputation. The approach uses an iterative algorithm to achieve an interactive linear FE deformation simulation.

[Suvranu De, Dhannanjay Deo, Ganesh Sankaranarayanan, Venkata S. Arikatla, 2011] presents PhyNNeSS - a physics-driven neural networks-based simulation system - that can simulate hyperelastic biological organs in realtime (both realtime graphics and realtime haptics) by making use of artificial neural networks.

[Jacob Rosen, Blake Hannaford, Christina G. Richards, Mika N. Sinanan, 2001] develops and assess a skill scale using Markov models (MMs). The skill scale can be used to evaluate surgeons or surgical simulators. The Markov Modeling that is employed to model the minimally invasive surgery uses tool/tissue interaction and force/torque signatures.

[Wing Kam Liu, Yaling Liu, David Farrell, Lucy Zhang, X. Sheldon Wang, Others, 2006] summarizes the newly developed Immersed Finite Element Method (IFEM); the proposed method is used to study the fluid-structure interaction problems as encountered in human cardiovascular systems.

[Jerzy Smolen, Alexandru Patriciu, 2009] deals with the deformation planning for robotic soft tissue manipulation. In this work, the Reproducing Kernel Particle Method (RKPM) is also made use of.

[M. Foroutan, H. Dalayeli, M. Sadeghian, 2007] deals with the simulation of large deformations of rubbers by the RKPM method; here, hyperelastic material behavior is assumed.

[N R B Krishnam Raju, J Nagabhushanam, 2000] extends the integrated force method to nonlinear structural analysis. It demonstrates that the integrated force method is equally viable and efficient as compared to the displacement method, when it comes to the analysis of nonlinear structures.

[Guillaume Picinbono, Herve Delingette, Nicholas Ayache, 2003] proposes a new deformable model based on non-linear elasticity, anisotropic behavior, and the finite element method. The model is valid for large displacements, and the model can address the problem of volume variations by using incompressibility constraints.

[Jun Wang, Hua Li, 1994] proposes recurrent neural networks for solving simultaneous linear algebraic equations; a circuit schematic for realizing the neural networks is also described.

[ZHU Qing, ZHANG Yeting, LI Fengchun, 2008] proposes a new algorithm for the automatic generation of three dimensional triangulated irregular network (TIN) from a point cloud. The reference mentions that the algorithm has potential applications to virtual environments.

[Jean-Claude Latombe, 1999] is a research proposal submitted to the NSF. It aims to model human soft tissues for surgical applications, mainly using spring-mass models. The unique features that the research aims to achieve are: modeling of complex tissue structures, realistic modeling of the mechanical response of individual tissues, modeling changes in tissue topology, dynamic simulation, automatic construction of tissue models.

[Yi–Je Lim, John Hu, Chu-Yin Chang, Neil Tardella, 2006] presents a realistic surgery simulation technique that includes new algorithms for simulating surgical palpation and cutting. The point-associated finite field (PAFF) modeling technique - which is a meshfree computational scheme - is used during the simulation. The simulation is inherently nonlinear because of the necessity of simulating cutting.

[Yazdan Shirvany, Mohsen Hayati, Rostam Moradian, 2009] presents a novel method for the numerical solution of ordinary and partial differential equations. The method utilizes MultiLayer Perceptron and Radial Basis Function (RBF) neural networks with a novel unsupervised training method.

[M. Kauer, V. Vuskovic, J. Dual, G. Szekely, M. Bajka, 2002] deals with the inverse finite element characterization of soft tissues.

[James T. Hing, Ari D. Brooks, Jaydev P. Desai, 2007] presents a methodology for modeling the needle and soft-tissue interaction during needle insertion. A biplanar fluoroscopic approach is used for the measurement, modeling, and simulation.

[Y. Tillier, A. Paccini, M. Durand-Reville, F. Bay, J.-L. Chenot, 2003] presents a new approach based on three-dimensional finite element software and an elastic constitutive equation, which is able to predict realistic results; the goal is to simulate the deformation of soft tissues, namely lamb kidney and human uterus, during laparoscopic surgery.

[G. Szekely, Ch. Brechbuhler, R. Hutter, A. Rhomberg, N. Ironmonger, P. Schmid, 2000] aims to develop a framework for the full-scale, real-time, finite element simulation of elastic tissue deformation in complex systems such as the human abdomen, with the intention of implementing the developed techniques in a gynecological laparoscopic VR-trainer system.

[Davide Valtorta, Edoardo Mazza, 2005] introduces a new method for the dynamic measurement of soft tissue viscoelastic properties; the method makes use of a torsional resonator device.

[Evren Samur, Mert Sedef, Cagatay Basdogan, Levent Avtan, Oktay Duzgun, 2005] reports the development of a robotic indenter for minimally invasive measurement of tissue properties during a laparoscopic surgery. From the experimental results, Young's modulus of pig liver is estimated to be around 15 kPa; it is also observed that pig liver shows linear viscoelastic behavior.

[Javad Dargahi, Siamak Najarian, Bin Liu, 2007] deals with the sensitivity analysis (both experimental and theoretical) of a novel tactile probe for measurement of tissue softness with applications in robotic surgery.

[Safdar N. Khan, Joseph M. Lane, 2004] gives an account of animal models for tissue-engineered bone constructs, as applied to spinal fusion surgery.

[R. Sierra, M. Bajka, G. Szekely, 2006] investigates different methods for the generation of tumor models suitable for surgical training simulators, hysteroscopy simulator in particular. A cellular automaton and a particle based tumor growth model are looked into.

[Kim V. Hansen, Lars Brix, Christian F. Pedersen, Jens P. Haase, Ole V. Larsen, 2004] models the interaction between a spatula and a human brain. The aim is to provide surgeons with a tool that can teach them the correlation between deformation and applied force. Here, a finite element based model of the brain is utilized in a Virtual Reality setup.

[Shigeyuki Suzuki, Naoki Suzuki, Makoto Hashizume, Yoshihiro Kakeji, Kozo Konishi, Asaki Hattori, Mitsuhiro Hayashibe, 2004] describes the development of the tele-training simulator that enables a surgeon to master and practice the techniques for robotic surgery, the robotic surgery system "da Vinci" in particular. A sphere-filled model is used to model soft tissue and the "PHANToM" is used as the haptic device. The reference suggests that by using the broadband line via the Internet, one can perform the tele-virtual training simulation using the simulator.

[Kup-Sze Choi, Hanqiu Sun, Pheng-Ann Heng, 2004] presents an efficient and scalable deformable model for virtual reality based medical applications. Simulated annealing (SA) algorithms are developed to optimize the model parameters by making use of the reference data generated with the finite element method.

[P. Wang, A.A. Becker, I.A. Jones, A.T. Glover, S.D. Benford, C.M. Greenhalgh, M. Vloeberghs, 2006] presents a virtual-reality surgical simulator aimed at neurosurgery. The simulator uses the boundary element method together with precomputations to achieve the realtime performance; linear elastic material behaviour is assumed. Cutting can also be simulated in this simulator.

[Kup-Sze Choi, 2006] deals with the interactive cutting of deformable objects using force propagation approach and digital design analogy. The approach uses a spring-mass system, and a systematic method is proposed to trace and manage the topology changes during interactive cutting; the dynamics of deformable objects and the cutting induced deformation are simulated by the force propagation among the mass-points.

[U. Meier, O. Lopez, C. Monserrat, M. C. Juan, M. Alcaniz, 2005] presents a classification of the different deformable models available in literature, and it also presents the advantages and disadvantages of each of the models. Also, the reference makes a comparison of the different deformable models, performs an evaluation of the state of the art, and discusses the future of deformable models.

[Shigeyuki Suzuki, Naoki Suzuki, Mitsuhiro Hayashibe, Asaki Hattori, Kozo Konishi, Yoshihiro Kakeji, Makoto Hashizume, 2005] deals with tele-surgery simulation to perform surgical training of abdominal da Vinci surgery. The reference develops a surgery simulation that provides a method of training and mastering surgical procedures (a cholecystectomy in particular) with the da Vinci system. The system aims to construct a training simulation center that will enable a surgeon to simulate surgery from or in remote places, to collaborate remotely, and to provide guidance from expert surgeons. The soft tissue model is created by the sphere-filled method enabling realtime deformations based on a patient's data.

[D. Bielser, P. Glardon, M. Teschner, M. Gross, 2004] proposes a state machine for real-time cutting of tetrahedral meshes.

[Ivan Porro, Andrea Schenone, Marco Fato, Edoardo Raposio, Elisa Molinari, Francesco Beltrame, 2005] reports the development of an integrated environment for plastic surgery support, and discusses the details like building virtual patients, simulating interventions, and supporting intraoperative decisions. The system allows surgical simulation, planning, and support for computer-guided plastic surgery procedures starting from image acquisition to final intraoperative assistance. The system also provides the user with a radiological workstation that is able to analyze patient medical images and case studies, with advanced two dimensional and three dimensional image processing capabilities.

[Arne Radetzky, Andreas Nurnberger, 2002] presents suitable visualization and simulation methods for surgical simulation utilizing actual patient's datasets. A neuro-fuzzy system is described, which can be used for the simulation of interactive tissue deformations; the neuro-fuzzy system makes it possible to define the deformation behavior based on a linguistic description of the tissue characteristics or to learn the dynamics by using measured data of real tissue.

[M.E.H. Eltaib, J.R. Hewit, 2003] is a review paper that reviews artificial tactile sensing systems for minimal access surgery (MAS). The technology is addressed from different viewpoints like tactile sensing, tactile data processing, and tactile display. The review paper assumes importance because restoring tactile capability to MAS surgeons (since the "sense of feel" that is used routinely in open surgery is lost in MAS) by artificial means brings immense benefits in patient welfare and safety.

[F.J. Carter, T.G. Frank, P.J. Davies, D. McLean, A. Cuschieri, 2001] deals with measurements and modelling of the compliance of human and porcine organs. Experiments showed that pig spleen is much more compliant than pig liver with mean elastic moduli of 0.11 and 4.0 MPa respectively. Also, it was found that the right lobe of human liver had a mean elastic modulus of about 0.27 MPa. However, it was found that a single case of a diseased liver had a mean modulus of 0.74 MPa — nearly three times the stiffness. It was also found that an exponential stress–strain law could accurately fit uniform stress test data and that subsequent finite element modelling for non-uniform stress around a small indentor matched measured force characteristics.

[Christos Trantakis, Friedrich Bootz, Gero Straub, Edgar Nowatius, Dirk Lindner, Husssein Cakmak, Heiko Maab, Uwe Kuhnapfel, Jurgen Meixensberger, 2003] presents a new system for neurosurgical training that enables virtual endoscopy with force feedback.

[Jan Sigurd Rotnes, Johannes Kaasa, Geir Westgaard, Eivind Myrold Eriksen, Per Oyvind Hvidsten, Kyrre Strom, Vidar Sorhus, Yvon Halbwachs, Ole Jakob Elle, Erik Fosse, 2001] demonstrates the possibility of obtaining surgical simulation on a standard PC Linux system by integrating free-form geometry data structures integrated with spring-mass tissue models. The paper claims that the technology also makes benefits when simulation is to be used over a network with limited bandwidth, especially when it comes to handling of soft tissue dynamics.

[U. Meier, F.J. Garcia, N.C. Parr, C. Monserrat, J.A. Gil, V. Grau, M.C. Juan, M. Alcaniz, 2001] presents a general surgery simulator for training surgeons in minimally invasive surgery. The simulator provides force feedback also, providing the surgeon with a sense of touch also. In this simulator, the virtual environments are optionally composed of an actual patient's organs the intervention on which one desires to practice in a beforehand manner, or of synthetically generated organs with arbitrary pathologies.

[Jason S. Lewis, S. Achilefu, J.R. Garbow, R. Laforest, M.J. Welch, 2002] is a review paper focused on three modalities, PET, MR and optical imaging which are avaliable to the scientist for oncological investigations in animals.

[Hayes B. Gladstone, Gregory J. Raugi, Daniel Berg, Jeff Berkley, Suzanne Weghorst, Mark Ganter, 2000] gives a general overview of virtual reality of the 21st century, together with a specific focus on dermatologic surgery. The reference also reports the development of a virtual reality soft tissue surgery simulator; based on fast finite element modeling and using a personal computer, the simulator can simulate three-dimensional human skin deformations with real-time tactile feedback.

[M.A.F. Rodrigues, D.F. Gillies, P. Charters, 1998] deals with modelling and simulation of the tongue during laryngoscopy.

[Konstantinos Moutsopoulos, Duncan Gillies, 1997] deals with deformable models for laparoscopic surgery simulation.

[A. C. M. Dumay, G. J. Jense, 1995] discusses on the topic of endoscopic surgery simulation in a virtual environment. The paper tries to answer the question: "Can virtual environment technology assist surgeons in training and maintaining endoscopic surgery skills?" The paper opines that virtual environment technology has great potential for surgical training purposes.

[Herve Delingette, Nicholas Ayache] gives some interesting facts about surgical simulators in the beginning. For example, the reference notes that the concept of surgery simulation, in the beginning, was in large part advocated by the American Department of Defense, as a key part of their vision of the future of emergency medicine; the reference notes that the development of commercial simulators has proved that there is a demand for products that help to optimize the learning curve of surgeons; the reference mentions that the emergence of medical robotics and more precisely of minimally invasive surgery robots, has reinforced the need for simulating surgical procedures, since these robots require a very specific hand-eye coordination; the reference also mentions that the modeling of living tissue, and their ability to deform under the contact of an instrument is one of the important aspect of simulators that should be improved. Next, the reference presents different algorithms for modeling soft tissue deformation in the context of surgery simulation.

[Yongmin Zhong, Bijan Shirinzadeh, Julian Smith, Chengfan Gu, 2009] proposes an improved reaction–diffusion model (which is an electromechanical based deformable model) to describe the distribution of the mechanical load in soft tissues, and a three-layer artificial cellular neural network is used to solve the reaction–diffusion model for real-time simulation of soft tissue deformation. The proposed model can accommodate isotropic, anisotropic and inhomogeneous deformations just by modifying diffusion coefficients.

[Sarthak Misra, K. T. Ramesh, Allison M. Okamura, 2008] is a review paper that classifies the existing research on tool-tissue interactions for surgical simulators based on the modeling techniques employed and the kind of surgical operation being simulated.

[Jung Kim, Mandayam A. Srinivasan, 2005] characterizes the nonlinear viscoelastic properties of intra-abdominal organs using the data from in vivo animal experiments and an inverse FE parameter estimation algorithm. While assuming quasi-linear-viscoelastic theory, the reference estimates the viscoelastic and hyerelastic material parameters to provide a physically based simulation of tissue deformations. The reference also reports that one can successfully reduce the time and computational resources by decoupling the viscoelastic part and nonlinear elastic part in the tissue model.

[Jung Kim, Bummo Ahn, Suvranu De, Mandayam A. Srinivasan, 2008] assumes that the soft tissues obey quasi-linear-viscoelastic theory, and the material parameters are estimated using an inverse FE parameter estimation algorithm. An approach that decouples the viscoelastic part and the nonlinear elastic part in a tissue model is also used to improve the performance of computations.

[Basdogan C., 2001] presents two efficient methods for the realtime simulation of dynamically deformable objects that are modeled by the finite element method. The first method uses modal analysis whereas the second method uses the spectral Lanczos decomposition. Both the methods lead to faster solutions when compared to standard methods that are based on the direct numerical integration.

[Ahn B., Kim J., 2010] records the surface deformation and force response of porcine livers undergoing large deformations through indentation experiments, using a three-dimensional (3D) optical system and a force transducer. An inverse FEM optimization algorithm is used to estimate the model parameters assuming hyperelastic and linear viscoelastic material behavior.

[Firat Dogan, M. Serdar Celebi, 2011] informs that, to date, standard non-linear finite-element methods are incapable of providing the real-time performance needs. To adress the problem, the reference proposes a new hybrid technique that acts on the reduced order static model acquired through a model reduction technique; the dynamic behavior is then obtained by overlaying pre-calculated displacement responses of surface nodes accounting for the time-dependent viscoelastic properties.

[Ashley Horton, Adam Wittek, Karol Miller] proposes an algorithm based on the Element Free Galerkin method, Total Lagrangian explicit dynamics, and nonlinear material formulation; since the proposed algorithm does not require a finite element mesh, it is well suited to simulations with irregular geometry. Also, a 3D simulation of craniotomy induced brain shift is presented.

[Karol Miller, 1999] proposes a large deformation linear viscoelastic model that is suitable for direct use with commercially available finite element software packages like ABAQUS. The proposed constitutive equation is of polynomial form with time-dependent coefficients; the model requires four material constants.

[Karol Miller, Kiyoyuki Chinzei, 2002] contains experimental results of in-vitro uniaxial tensile test of swine brain tissue in finite deformation; it also proposes a new hyper-viscoelastic constitutive model for the brain tissue.

[Teerandoot Chanthasppeephan, Jaydev P. Desai, Alan C. W. Lau, 2003] models the liver cutting process by experimentally determining the mechanical properties, and develops a constitutive model that is consistent with the experimentally determined properties.

[C. Mendoza, C. Laugier, 2003] proposes a physical model of cutting that uses a large displacement (Green) strain tensor formulation; explicit finite elements are used to achieve real-time simulations and fast topology updates during cutting simulations.

[Mohsen Mahvash, Vincent Hayward, 2001] discusses haptic rendering of cutting.

[Amy E. Kerdok, Simona Socrate, Robert D. Howe, 2004] presents preliminary results from large strain creep tests carried out on ex-vivo whole liver, using a perfusion system that mimics in vivo conditions; a description of the proposed constitutive model is also presented.

[Alessandro Nava, Edoardo Mazza, Oliver Haefner, Michael Bajka, 2004] presents experiments on soft tissues that show the evolution of the mechanical response during a series of loading and unloading cycles.

[Rhomberg A., Enzler R., Thaler M., Troster G., 1998] discusses the design of a FEM computation engine for real-time laparoscopic surgery simulation; it also provides some quantitative measurements of the computation and communication times; the SGI Onyx2 parallel computer is used in the study.

[Herve Delingette, 1998] surveys existing deformation models (like spring models, implicit models, finite element models) in medical simulation, and analyzes the obstacles to combining computer-graphics representations with biomechanical models. In particular, the different geometric representations of deformable bodies are compared in relation to the tasks of real-time deformation, tissue cutting, and force-feedback interaction.

[Cagatay Basdogan, Suvranu De, Jung Kim, Manivannan Muniyandi, Hyun Kim, Mandayam A. Srinivasan, 2004] discusses main aspects of haptics in minimally invasive surgical simulation and training, like haptic rendering, haptic recording, and haptic playback.

[Guillaume Picinbono, Herve Delingette, Nicholas Ayache, 2001] proposes a new deformable model that is based on non-linear elasticity and the finite element method; the model is valid for large displacements and anisotropic behavior and this improves the realism of the deformations. The reference also demonstrates the relevance of the model for the real-time simulation of laparoscopic surgical procedures on liver.

[Mendoza C., Laugier C., 2003] presents a methodology to simulate cuts in deformable objects. It proposes a simple physical model of cutting that uses a large displacement (Green) strain tensor formulation; cutting is achieved by separating the tetrahedrons that make up the object; explicit finite elements are used to allow real-time simulations and to allow fast topology updates during cutting procedures. Also, force-feedback is added to increase realism.

[Ichitsubo K., Tanifuji T., 2005] proposes the finite difference time domain (FDTD) analysis that is based on nonuniform grids, for solving the equations governing diffusion in biological tissues.

Literature on numerical methods

[Shaofan Li, Wing Kam Liu, 2002] is a review article upon meshfree and particle methods and their applications in applied mechanics; it includes 397 references.

[Andras Sobester, Prasanth B. Nair, Andy J. Keane, 2008] proposes a technique that is based on genetic programming for the meshfree solution of elliptic partial differential equations; it employs the least-squares collocation principle for defining an objective function that is optimized using genetic programming.

[Lagaris I. E., Likas A., Fotiadis D. I., 1998] presents a method for solving initial and boundary value problems; the method makes use of artificial neural networks.

[A. Nagarajan, E. Lutz, S. Mukherjee, 1994] presents a novel method called Boundary Contour Method. The method requires no numerical integration at all for two-dimensional problems and requires only the numerical evaluation of line integrals for three-dimensional problems, even for curved line or surface boundary elements of arbitrary shape.

[A. Nagarajan, S. Mukherjee, E. Lutz, 1996] applies the Boundary Contour Method to three-dimensional linear elasticity problems. Here, the surface integrals on boundary elements of the usual boundary element method are transformed into line integrals on the bounding contours of these elements, through an application of Stokes' theorem. Thus, only line integrals have to be numerically evaluated for three-dimensional elasticity problems - even for curved surface elements of arbitrary shape.

[K.Y. Sze, X.H. Liu, S.H. Lo, 2004] identifies eight popularly employed benchmark problems, and their detailed reference solutions are obtained and tabulated. The solutions can form a convenient basis for subsequent comparison, and the availability of reference solutions can avoid the tedious yet inaccurate task of reconstructing data points by graphical measurement of previously reported load–deflection curves. Also, the relative convergent difficulty of each of the problems are revealed by the number of load increments and the total number of iterations required by an automatic load incrementation scheme for attaining the converged solutions under the maximum loads.

[S. S. Kulkarni, S. Telukunta, S. Mukherjee, 2003] deals with the coupling of the boundary node method (BNM) and the multipole method (MM), in the context of 2-D potential theory.

[Gang Li, N.R. Aluru, 2002] presents a boundary cloud method (BCM) for boundary-only analysis of partial differential equations that can solve potential equations in two dimensions (2-D). The BCM uses a weighted least-squares approach for construction of interpolation functions, and it uses a boundary integral formulation for the governing equations.

[G.R. Liu, Y.T. Gu, 2004] discusses boundary meshfree methods based on the boundary point interpolation methods.

[S. De, K. J. Bathe, 2000] presents a new technique named "Method of Finite Spheres".

[Suvranu De, Klaus-Jurgen Bathe, 2001a] deals with the proper choice of the interpolation scheme, numerical integration procedures, and techniques of imposing boundary conditions, in the context of the method of finite spheres.

[Suvranu De, Klaus-Jurgen Bathe, 2001b] tackles the problem of volumetric 'locking' when incompressible or nearly incompressible deformations are encountered in the method of finite spheres; it uses a displacement-pressure mixed formulation.

[Suvranu De, Klaus-Jurgen Bathe, 2001c] reports several new numerical integration rules for the method of finite spheres; the new rules result in significant reduction in computational costs.

[Yi-Je Lim, Suvranu De, 2007] extends the point collocation-based method of finite spheres (PCMFS) technique to geometrically nonlinear tissue deformations. The approach is based on a novel combination of multi-resolution approach that is coupled with a fast reanalysis scheme in which the response predicted by an underlying linear PCMFS model is enhanced in the local neighborhood of the surgical tool-tip by a nonlinear model.

[Suleiman BaniHani, Suvranu De, 2006] develops a technique in which the integration points and weights for the method of finite spheres are generated using genetic algorithms and stored in a lookup table using normalized coordinates as part of an offline computational step; and during online computations, the lookup table is used much like a table of Gaussian integration points and weights in the finite element computations. The technique offers significant reduction of computational time without compromising on accuracy.

[Michael Macri, Suvranu De, Mark S. Shephard, 2003] reports the development of a geometry-based automatic pre-processing environment for the method of finite spheres; techniques of generating open covers for the Galerkin-based as well as the point collocation-based method of finite spheres are presented for two-dimensional and three-dimensional problems by recursive spatial subdivision using quadtrees and octrees, respectively.

[Michael Macri, Suvranu De, 2005] reports the development of a geometry-based automatic preprocessing environment and efficient numerical integration schemes for the method of finite spheres. In addition, several techniques of coupling the method of finite spheres with the traditional finite element schemes are presented; coupling the method of finite spheres with the finite element schemes is found to improve computational efficiency and facilitate the imposition of Dirichlet boundary conditions.

[E. Onate, F.Perazzo, J. Miquel, 2001] describes a method called the Finite Point Method (FPM) for the fully meshless solution of elasticity problems; a stabilization technique based on finite calculus is used to improve the quality of the numerical solution.

[A. Sadeghirad, S. Mohammadi, 2007] proposes a truly meshless approach for the imposition of Neumann boundary conditions in the FPM, and adopts the approach for 2D elasticity analyses. In the proposed approach, equilibrium on lines on the Neumann boundary conditions is satisfied as Neumann boundary condition equations. Numerical studies show that the approach is simple to implement and computationally efficient and also leads to more stable and accurate results.

[W. X. Wang, Y. Takao, 2004] presents a new truly meshless method called the isoparametric finite point method (IFPM). IFPM is developed based on the concepts of meshless discretization and local isoparametric interpolation; the unknown functions, their derivatives, and the sub-domain and its boundaries of an arbitrary point are described by the same shape functions.

[B. Boroomand, A. A. Tabatabaei, E. Onate, 2005] presents a stabilized version of the finite point method (FPM) while discussing a source of instability due to the evaluation of the base function using a least square procedure; a suitable mapping is proposed and employed to eliminate the ill-conditioning effect due to directional arrangement of the points.

[Eugenio Onate, 2003] introduces a general procedure for the computational analysis of a wide class of multi-scale problems in mechanics using a finite calculus (FIC) formulation.

[Eugenio Onate, 2004] discusses the possibilities of the finite calculus method for the finite element solution of these problems: convection–diffusion problems with sharp gradients, incompressible fluid flow, incompressible solid mechanics problems, strain localization situations.

[Eugenio Onate, Julio Garcia, Sergio Idelsohn, 1997] provides an expression for the element stabilization parameter (for stabilized finite element schemes) in terms of the solution residual and its first derivatives in an iterative or adaptive manner.

[L. Perez Pozo, F. Perazzo, A. Angulo, 2009] presents a methodology that uses the meshless finite points method for the analysis of nonlinear material problems with proportional loading based on deformation theory.

[G. Yagawa, T. Yamada, 1996] proposes a new meshless finite element method that is named as the Free Mesh Method. Here, temporary triangular elements are set around a node, i.e. a current central node; the contributions from the element matrices are assembled to the total stiffness matrix. The process is repeated for all the nodes in the domain. Finally, the solution is obtained by solving the total stiffness equation system as in the usual finite element method.

[Genki Yagawa, Tomonari Furukawa, 2000] presents improvements to the Free Mesh Method; goal is to improve accuracy.

[Tomonari Furukawa, Changqi Yang, Genki Yagawa, Chang-Chun Wu, 2000] presents the formulation of free mesh method and presents two approaches of the method by incorporating quadrilateral elements. The first approach creates quadrilateral elements inside every triangular element whereas quadrilateral elements are generated outside every triangular element in the second approach. Results of numerical examples indicate that the two approaches improve the accuracy of free mesh method.

[L. Gavete, M.L. Gavete, J.J. Benito, 2003] gives a procedure which can easily assure the quality of numerical results by obtaining the residual at each point, in the context of the generalized finite difference (GFD) method. The possibility of employing the GFD method over adaptive clouds of points while increasing progressively the number of nodes is explored, giving in this paper a condition to be accomplished to employ the GFD method with more efficiency. Also, the GFD method is compared with another meshless method called the element free Galerkin method (EFG).

[T. Liszka, J. Orkisz, 1980] presents a modification of the Finite Difference Method which enables local condensation of the mesh and easy discretization of the boundary conditions in the case of a domain of arbitrary shape. Also, several problems arising from the use of an irregular mesh have been solved, the most important being elimination of singular or ill-conditioned stars. A successful way of automatic discretization of boundary conditions is also proposed.

[C. Monserrat, U. Meier, M. Alcaniz, F. Chinesta, M.C. Juan, 2001] tells that establishing deformable models with BEM is a reliable method to model objects in virtual reality environments for surgical simulations. In addition, the elasticity parameters are obtained experimentally through the use of a pig's liver.

[M. Kreienmeyer, E. Stein, 1995] deals with the parallel implementation of the boundary element method (BEM) for linear elastic 2D-problems on a MIMD parallel computer.

[Ullrich Meier, Carlos Monserrat, Nils-Christian Parr, Francisco Javier Garcia, Jose Antonio Gil, 2001] uses a boundary element (BEM) based algorithm to simulate incisions on an organ in real time.

[I. Prieto, A.L. Iban, J.A. Garrido, 1999] proposes a boundary element method (BEM) approach for the solution of the 2D elastic problem considering geometric non-linearities. Geometric non-linearities considered are both finite strains and large displacements; material non-linearities are not considered.

[G. R. Liu, Jian Zhang, K. Y. Lam, Hua Li, G. Xu, Z. H. Zhong, G. Y. Li, X. Han, 2008] presents a new gradient smoothing method (GSM) in which a gradient smoothing along with a directional derivative technique is used to develop the first- and second-order derivative approximations for a node of interest by systematically computing weights for a set of surrounding field nodes. Then a simple collocation procedure is used to the governing strong-from of system of equations at each node scattered in the problem domain using the approximated derivatives.

[S. N. Atluri, T. Zhu, 1998] presents a new meshfree technique named Meshless Local Petrov-Galerkin (MLPG), for computational mechanics.

[S. N. Atluri, H.-G. Kim, J. Y. Cho, 1999] critically examines the salient features of the Meshless Local Petrov-Galerkin (MLPG) method and of the Local Boundary Integral Equation (LBIE) method from the points of view of a non-element interpolation of the field variables and of the meshless numerical integration of the weak form used to generate the stiffness matrix.

[S. N. Atluri, J. Y. Cho, H.-G. Kim, 1999] generalizes the conventional moving least squares interpolation scheme with the intention of incorporating the information concerning the derivative of the field variable into the interpolation scheme. Here, by using this generalized moving least squares interpolation along with the MLPG (Meshless Local Petrov-Galerkin), a new numerical approach is proposed to deal with 4th order problems of thin beams.

[I. S. Raju, D. R. Phillips, T. Krishnamurthy, 2004] presents a meshless local Petrov-Galerkin (MLPG) method that uses radial basis functions in stead of generalized moving least squares (GMLS) interpolations to develop the trial functions in the study of Euler-Bernoulli beam problems.

[Satya N. Atluri, Shengping Shen, 2005] surveys the developments and applications of the MLPG methods; several variations of the meshless interpolation schemes are reviewed also. The interrelation of the various meshless approaches is presented too.

[Satya N. Atluri, Shengping Shen, 2002] makes a comparative study of the efficiency and accuracy of different meshless methods arising out of the use of different trial and test functions under the frame work of the meshless local Petrov-Galerkin (MLPG) method; it also predicts that MLPG, due to its speed, accuracy and robustness, may be expected to replace the FEM in the near future.

[Xi Zhang, Zhenhan Yao, Zhangfei Zhang, 2006] presents two-dimensional large deformation analysis of hyperelastic and elasto-plastic solids based on the Meshless Local Petrov–Galerkin method (MLPG).

[Z. D. Han, A.M. Rajendran, S.N. Atluri, 2005] develops a nonlinear formulation of the Meshless Local Petrov-Galerkin (MLPG) finite-volume mixed method for the large deformation analysis of static and dynamic problems; here, the velocity gradients are interpolated independently to avoid the time consuming differentiations of the shape functions at all integration points.

[Z. D. Han, S. N. Atluri, 2004] develops three different truly Meshless Local Petrov-Galerkin (MLPG) methods for solving 3D elasto-static problems; here, using the general MLPG concept, the methods are derived through the local weak forms of the equilibrium equations by using different test functions, namely, the Heaviside function, the Dirac delta function, and the fundamental solutions. Numerical examples demonstrate that the methods are very promising for solving the elastic problems when compared to the traditional Galerkin Finite Element Method.

[Q. Li, S. Shen, Z. D. Han, S. N. Atluri, 2003] develops a truly meshless method called the Meshless Local Petrov-Galerkin (MLPG) Method for three-dimensional elastostatics; the reference also states that the method holds a great promise to replace the finite element method in three-dimensional analysis in the near future.

[Su Hao, Harold S. Park, Wing Kam Liu, 2002] presents the fundamental concepts behind the moving particle finite element method which combines salient features of the finite element method and meshfree methods. The reference claims that the proposed method alleviates some problems that plague meshfree techniques such as essential boundary condition enforcement and the use of a separate background mesh to integrate the weak form; also, the method is illustrated via two-dimensional linear elastic problems.

[G.R. Liu , Y.T. Gu, 2003] proposes a new matrix triangularization algorithm (MTA) for overcoming the singularity problem in the point interpolation method (PIM) using the polynomial basis and to ensure stable and reliable construction of PIM shape functions. The algorithm is implemented in the local point interpolation method (LPIM) which is a truly meshfree method based on a local weak form. Numerical examples demonstrate that LPIM using the MTA is very easy to implement, and very robust for solving problems of computational mechanics.

[N. Sukumar, B. Moran, T. Belytschko, 1998] presents the application of the Natural Element Method (NEM) to boundary value problems in two-dimensional small displacement elastostatics; in the Natural Element Method, trial and test functions are constructed using natural neighbour interpolants, and these interpolants are based on the Voronoi tessellation of the set of nodes N.

[Enrique Pardo, 2000] presents a Path Integral (PI) formulation of linear elastostatics. Here, Navier equations are modified by adding a fictitious 'time' derivative of displacements so that equilibrium corresponds to the steady state of the resulting diffusion-like equations; the evolution of displacement is then represented as the propagation, through the fictitious time co-ordinate, of an initial displacement field corresponding to the unloaded state. The resulting procedure somehow mimics the well-known Feynman path integral of quantum mechanics, which is equivalent to the differential formulation embodied in Schrodinger equation.

[Enrique Pardo, 2002] addresses convergence rate and accuracy of a numerical technique for linear elastostatics based on a path integral formulation.

[Enrique Pardo, 2003] shows how blurred derivatives may be used to approximate differential equations and to re-express them in alternative ways. The reference shows that the blurred derivatives provide higher flexibility for selection of approximation functions than strong and weak formulations; also, some computational implementations of one-dimensional problems are discussed, and the relationship between several well-known numerical methods is analyzed. Finally a meshless numerical scheme for the Poisson equation is described in detail, and its performance is compared with linear finite elements and generalized finite differences on unstructured meshes of points.

[Enrique Pardo, 2005] shows that self-consistent boundary conditions for numerical methods that are based on blurred derivatives can be derived from a suitable change of variables of the fundamental blurred approximation of the differential equation, followed by application of Leibnitz theorem for differentiation of an integral. Also, a number of well-known computational methods are shown to be derivable from adequate manipulation of the blurred derivative technique; the simplest scheme obtained resembles the weak Local Petrov-Galerkin approximation.

[E. Pardo, 2003] shows that classical wave equations admit path integral formulations.

[Wing Kam Liu, Weimin Han, Hongsheng Lu, Shaofan Li, Jian Cao, 2004], [Shaofan Li, Hongsheng Lu, Weimin Han, Wing Kam Liu, Daniel C. Simkins, 2004], [Hongsheng Lu, Shaofan Li, Daniel C. Simkins Jr., Wing Kam Liu, Jian Cao, 2004], [Daniel C. Simkins Jr., Shaofan Li, Hongsheng Lu, Wing Kam Liu, 2004] introduce and analyze a new class of methods, collectively called the reproducing kernel element method (RKEM).

[ZHANG Ji-fa, ZHANG Wen-pu, ZHENG Yao, 2005] presents applications of Reproducing Kernel Particle Method (RKPM) inelasto-plastic problems after a review of meshfree methods and an introduction to RKPM; a slope stability problem in geotechnical engineering is analyzed as an illustrative case.

[Sukky Jun, Wing Kam Liu, Ted Belytschko, 1998] presents the explicit Reproducing Kernel Particle Method (RKPM), and the application of the method to the simulations of large deformation problems. RKPM is a meshless method which does not need a mesh structure in its formulation; because of this mesh-free property, RKPM is able to simulate large deformation problems without remeshing which is often required for the mesh-based methods such as the finite element method.

[Jiun-Shyan Chen, Chunhui Pan, Cheng-Tang Wu, Wing Kam Liu, 1996] presents large deformation analysis of non-linear elastic and inelastic structures based on Reproducing Kernel Particle Methods (RKPM); the formulation considers hyperelastic and elasto-plastic materials since they represent path-independent and path-dependent material behaviors, respectively. The reference observes that, unlike the conventional finite element approach, the nodal spacing irregularity in RKPM does not lead to irregular mesh shape that significantly deteriorates solution accuracy.

Further, the reference observes that no volumetric locking was observed when applying non-linear RKPM to nearly incompressible hyperelasticity and perfect plasticity problems. Also, the reference reports that model adaptivity in RKPM could be accomplished simply by adding more points in the highly deformed areas without remeshing.

[Wang H., Li Guangyao, Han X., Zhong Zhi Hua, 2007] presents a parallel computational implementation of the reproducing kernel particle method (RKPM) for explicit 3D bulk forming simulation problems.

[G. R. Liu, Jian Zhang, Hua Li, K. Y. Lam, Bernard B. T. Kee, 2006] proposes a radial point interpolation based finite difference method (RFDM). Here, radial point interpolation using local irregular nodes is used together with the conventional finite difference procedure to achieve both the adaptivity to irregular domain and the stability in the solution that is often encountered in the collocation methods; also, least-square technique is adopted here, which leads to a system matrix with good properties such as symmetry and positive definiteness.

[Lara M. Vigneron, Jacques G. Verly, Simon K. Warfield, 2004] proposes the use of XFEM to model the deformations resulting from cutting through organ tissues. The reference notes that a key feature of XFEM is that material discontinuities through FEM meshes can be handled without mesh adaptation or remeshing, as would be required in regular FEM.

[J J Monaghan, 2005] is a review paper that discusses the theory and application of Smoothed Particle Hydrodynamics (SPH) since its inception in 1977.

[Larry D. Libersky, A.G. Petschek] formulates an elastic-perfectly-plastic constitutive model within the Smooth Particle Hydrodynamics (SPH) framework.

[Matthias Muller, Simon Schirm, Matthias Teschner] proposes an interactive method based on Smoothed Particle Hydrodynamics (SPH) to simulate blood as a fluid with free surfaces.

[Min Li, Yun-Hui Liu, 2005] presents force model for effectively simulating the interactions of the pulpal tissue with the endodontic tools, based on the smoothed particle hydrodynamics (SPH) method.

[Simone E. Hieber, Jens H. Walther, Petros Koumoutsakos] introduces particle based simulations of two different human organ materials modeled as linear viscoelastic solids; the constitutive equations for the material behavior are discretized using a particle approach based on the Smoothed Particle Hydrodynamics (SPH) method while the body surface is tracked using level sets. The accuracy of the original formulation is significantly enhanced by using a particle reinitialization technique that results in remeshed Smoothed Particle Hydrodynamics (rSPH).

References grouped

In this section, a few references picked from the last section are grouped into separate groups. For example, all those references (picked from the last section) that deal with the development of a simulator are grouped to one paragraph (sometimes related references may be grouped to more than one paragraph, but these paragraphs are placed together).

[Herve Delingette, 1998] surveys existing deformation models (like spring models, implicit models, finite element models) in medical simulation, and analyzes the obstacles to combining computer-graphics representations with biomechanical models. In particular, the different geometric representations of deformable bodies are compared in relation to the tasks of real-time deformation, tissue cutting, and force-feedback interaction. [Rhomberg A., Enzler R., Thaler M., Troster G., 1998] discusses the design of a FEM computation engine for real-time laparoscopic surgery simulation; it also provides some quantitative measurements of the computation and communication times; the SGI Onyx2 parallel computer is used in the study. [Mandayam A. Srinivasan, et al.] is a progress report from the Laboratory for Human and Machine Haptics, which reports the ongoing work in the lab. It touches upon such topics like biomechanics of touch (e.g., measurement of spatial pressure distribution on the human skin during tactile sensing of objects, video-microscopic investigation of primate fingertip mechanics, frequency response of human skin in vivo to mechanical stimulation, finite element models of the primate fingertip), sensorimotor psychophysics (e.g., tactile perception threshold measurements), haptic device development (e.g., tactile perception test apparatus), human computer interactions (e.g., collaborative haptics), medical applications (e.g., in vivo characterization of the mechanical behavior of soft tissues for surgical simulation, tool-tissue collision prediction, meshless simulation techniques, graphical rendering with point-based models, multi-rate rendering, role of fidelity of multimodal simulation in virtual reality based surgical training).

[Shigeyuki Suzuki, Naoki Suzuki, Makoto Hashizume, Yoshihiro Kakeji, Kozo Konishi, Asaki Hattori, Mitsuhiro Hayashibe, 2004] describes the development of the tele-training simulator that enables a surgeon to master and practice the techniques for robotic surgery, the robotic surgery system “da Vinci” in particular. A sphere-filled model is used to model soft tissue and the “PHANToM” is used as the haptic device. The reference suggests that by using the broadband line via the Internet, one can perform the tele-virtual training simulation using the simulator. [P. Wang, A.A. Becker, I.A. Jones, A.T. Glover, S.D. Benford, C.M. Greenhalgh, M. Vloeberghs, 2006] presents a virtual-reality surgical simulator aimed at neurosurgery. The simulator uses the boundary element method together with precomputations to achieve the realtime performance; linear elastic material behaviour is assumed. Cutting can also be simulated in this simulator. [Shigeyuki Suzuki, Naoki Suzuki, Mitsuhiro Hayashibe, Asaki Hattori, Kozo Konishi, Yoshihiro Kakeji, Makoto Hashizume, 2005] deals with tele-surgery simulation to perform surgical training of abdominal da Vinci surgery. The reference develops a surgery simulation that provides a method of training and mastering surgical procedures (a cholecystectomy in particular) with the da Vinci system. The system aims to construct a training simulation center that will enable a surgeon to simulate surgery from or in remote places, to collaborate remotely, and to provide guidance from expert surgeons. The soft tissue model is created by the sphere-filled method enabling realtime deformations based on a patient’s data. [Ivan Porro, Andrea Schenone, Marco Fato, Edoardo Raposio, Elisa Molinari, Francesco Beltrame, 2005] reports the development of an integrated environment for plastic surgery support, and discusses the details like building virtual patients, simulating interventions, and supporting intraoperative decisions. The system allows surgical simulation, planning, and support for computer-guided plastic surgery procedures starting from image acquisition to final intraoperative assistance. The system also provides the user with a radiological workstation that is able to analyze patient medical images and case studies, with advanced two dimensional and three dimensional image processing capabilities. [U. Meier, F.J. Garcia, N.C. Parr, C. Monserrat, J.A. Gil, V. Grau, M.C. Juan, M. Alcaniz, 2001] presents a general surgery simulator for training surgeons in minimally invasive surgery. The simulator provides force feedback also, providing the surgeon with a sense of touch also. In this simulator, the virtual environments are optionally composed of an actual patient's organs the intervention on which one desires to practice in a beforehand manner, or of synthetically generated organs with arbitrary pathologies. [Christos Trantakis, Friedrich Bootz, Gero Straub, Edgar Nowatius, Dirk Lindner, Husssein Cakmak, Heiko Maab, Uwe Kuhnapfel, Jurgen Meixensberger, 2003] presents a new system for neurosurgical training that enables virtual endoscopy with force feedback.

[Jan Sigurd Rotnes, Johannes Kaasa, Geir Westgaard, Eivind Myrold Eriksen, Per Oyvind Hvidsten, Kyrre Strom, Vidar Sorhus, Yvon Halbwachs, Ole Jakob Elle, Erik Fosse, 2001] demonstrates the possibility of obtaining surgical simulation on a standard PC Linux system by integrating free-form geometry data structures integrated with spring-mass tissue models. The paper claims that the technology also makes benefits when simulation is to be used over a network with limited bandwidth, especially when it comes to handling of soft tissue dynamics. [Hayes B. Gladstone, Gregory J. Raugi, Daniel Berg, Jeff Berkley, Suzanne Weghorst, Mark Ganter, 2000] gives a general overview of virtual reality of the 21st century, together with a specific focus on dermatologic surgery. The reference also reports the development of a virtual reality soft tissue surgery simulator; based on fast finite element modeling and using a personal computer, the simulator can simulate three-dimensional human skin deformations with real-time tactile feedback.

[Firat Dogan, M. Serdar Celebi, 2011] informs that, to date, standard non-linear finite-element methods are incapable of providing the real-time performance needs. To adress the problem, the reference proposes a new hybrid technique that acts on the reduced order static model acquired through a model reduction technique; the dynamic behavior is then obtained by overlaying pre-calculated displacement responses of surface nodes accounting for the time-dependent viscoelastic properties. [Basdogan C., 2001] presents two efficient methods for the realtime simulation of dynamically deformable objects that are modeled by the finite element method. The first method uses modal analysis whereas the second method uses the spectral Lanczos decomposition. Both the methods lead to faster solutions when compared to standard methods that are based on the direct numerical integration.

[M. Hauth, J. Gross, W. Straber, G.F. Buess, 2003] deals with soft tissue simulation that is based on measured data. It presents a finite element system based on a sophisticated material model which is better suited for dynamical computations when compared to the standard approaches. A hierarchical basis and a stabilized Runge-Kutta method are used to achieve fast and accurate simulations.

[S. De, J.-W. Hong, K. J. Bathe, 2003] reports the new developments and new applications of the method of finite spheres. In particular, it uses the method of finite spheres in a surgical simulator; the commercial finite element program 'ADINA' is also used in the work. [Suvranu De, Jung Kim, Yi-Je Lim, Mandayam A. Srinivasan, 2005] uses the point collocation-based method of finite spheres (PCMFS) for real time simulation of soft tissues during minimally invasive surgery (MIS). The reference also discusses the integration of the methodologies into a practical surgical simulation system. [Suleiman M. BaniHani, Suvranu De, 2009] makes a comparison of some model order reduction methods for fast simulation of soft tissue response while using the point collocation-based method of finite spheres.

[Suvranu De, Dhannanjay Deo, Ganesh Sankaranarayanan, Venkata S. Arikatla, 2011] presents PhyNNeSS - a physics-driven neural networks-based simulation system - that can simulate hyperelastic biological organs in realtime (both realtime graphics and realtime haptics) by making use of artificial neural networks.

[Wing Kam Liu, Yaling Liu, David Farrell, Lucy Zhang, X. Sheldon Wang, Others, 2006] summarizes the newly developed Immersed Finite Element Method (IFEM); the proposed method is used to study the fluid-structure interaction problems as encountered in human cardiovascular systems. [Guillaume Picinbono, Herve Delingette, Nicholas Ayache, 2003] proposes a new deformable model based on non-linear elasticity, anisotropic behavior, and the finite element method. The model is valid for large displacements, and the model can address the problem of volume variations by using incompressibility constraints. [Jean-Claude Latombe, 1999] is a research proposal submitted to the NSF. It aims to model human soft tissues for surgical applications, mainly using spring-mass models. The unique features that the research aims to achieve are: modeling of complex tissue structures, realistic modeling of the mechanical response of individual tissues, modeling changes in tissue topology, dynamic simulation, automatic construction of tissue models.

[Yi–Je Lim, John Hu, Chu-Yin Chang, Neil Tardella, 2006] presents a realistic surgery simulation technique that includes new algorithms for simulating surgical palpation and cutting. The point-associated finite field (PAFF) modeling technique - which is a meshfree computational scheme - is used during the simulation. The simulation is inherently nonlinear because of the necessity of simulating cutting.

[Y. Tillier, A. Paccini, M. Durand-Reville, F. Bay, J.-L. Chenot, 2003] presents a new approach based on three-dimensional finite element software and an elastic constitutive equation, which is able to predict realistic results; the goal is to simulate the deformation of soft tissues, namely lamb kidney and human uterus, during laparoscopic surgery. [G. Szekely, Ch. Brechbuhler, R. Hutter, A. Rhomberg, N. Ironmonger, P. Schmid, 2000] aims to develop a framework for the full-scale, real-time, finite element simulation of elastic tissue deformation in complex systems such as the human abdomen, with the intention of implementing the developed techniques in a gynecological laparoscopic VR-trainer system. [Kup-Sze Choi, Hanqiu Sun, Pheng-Ann Heng, 2004] presents an efficient and scalable deformable model for virtual reality based medical applications. Simulated annealing (SA) algorithms are developed to optimize the model parameters by making use of the reference data generated with the finite element method. [Guillaume Picinbono, Herve Delingette, Nicholas Ayache, 2001] proposes a new deformable model that is based on non-linear elasticity and the finite element method; the model is valid for large displacements and anisotropic behavior and this improves the realism of the deformations. The reference also demonstrates the relevance of the model for the real-time simulation of laparoscopic surgical procedures on liver.

[D. Bielser, P. Glardon, M. Teschner, M. Gross, 2004] proposes a state machine for real-time cutting of tetrahedral meshes. [Arne Radetzky, Andreas Nurnberger, 2002] presents suitable visualization and simulation methods for surgical simulation utilizing actual patient’s datasets. A neuro-fuzzy system is described, which can be used for the simulation of interactive tissue deformations; the neuro-fuzzy system makes it possible to define the deformation behavior based on a linguistic description of the tissue characteristics or to learn the dynamics by using measured data of real tissue. [Konstantinos Moutsopoulos, Duncan Gillies, 1997] deals with deformable models for laparoscopic surgery simulation. [Ashley Horton, Adam Wittek, Karol Miller] proposes an algorithm based on the Element Free Galerkin method, Total

Lagrangian explicit dynamics, and nonlinear material formulation; since the proposed algorithm does not require a finite element mesh, it is well suited to simulations with irregular geometry. Also, a 3D simulation of craniotomy induced brain shift is presented.

[C. Monserrat, U. Meier, M. Alcaniz, F. Chinesta, M.C. Juan, 2001] tells that establishing deformable models with BEM is a reliable method to model objects in virtual reality environments for surgical simulations. In addition, the elasticity parameters are obtained experimentally through the use of a pig's liver. [Ullrich Meier, Carlos Monserrat, Nils-Christian Parr, Francisco Javier Garcia, Jose Antonio Gil, 2001] uses a boundary element (BEM) based algorithm to simulate incisions on an organ in real time.

[Han-Wen Nienhuys, A. Frank van der Stappen, 2001] combines the Finite Element (FE) method and interactive cutting without requiring expensive matrix updates or precomputations. The approach uses an iterative algorithm to achieve an interactive linear FE deformation simulation. [Mendoza C., Laugier C., 2003] presents a methodology to simulate cuts in deformable objects. It proposes a simple physical model of cutting that uses a large displacement (Green) strain tensor formulation; cutting is achieved by separating the tetrahedrons that make up the object; explicit finite elements are used to allow real-time simulations and to allow fast topology updates during cutting procedures. Also, force-feedback is added to increase realism. [Mohsen Mahvash, Vincent Hayward, 2001] discusses haptic rendering of cutting.

[Kup-Sze Choi, 2006] deals with the interactive cutting of deformable objects using force propagation approach and digital design analogy. The approach uses a spring-mass system, and a systematic method is proposed to trace and manage the topology changes during interactive cutting; the dynamics of deformable objects and the cutting induced deformation are simulated by the force propagation among the mass-points. [Teerandoot Chanthasppeephan, Jaydev P. Desai, Alan C. W. Lau, 2003] models the liver cutting process by experimentally determining the mechanical properties, and develops a constitutive model that is consistent with the experimentally determined properties.

[Sarthak Misra, K. T. Ramesh, Allison M. Okamura, 2008] is a review paper that classifies the existing research on tool-tissue interactions for surgical simulators based on the modeling techniques employed and the kind of surgical operation being simulated. [Jerzy Smolen, Alexandru Patriciu, 2009] deals with the deformation planning for robotic soft tissue manipulation. In this work, the Reproducing Kernel Particle Method (RKPM) is also made use of. [Maud Marchal, Emmanuel Promayon, Jocelyne Troccaz, 2005] presents a new approach for soft tissue modelling which integrates the interactions between a given soft organ and its surrounding organs. The proposed model is applied to the simulation of the prostate-bladder set. The model is compared to the finite element method in order to quantify its performance and physical realism. [Ichitsubo K., Tanifuji T., 2005] proposes the finite difference time domain (FDTD) analysis that is based on nonuniform grids, for solving the equations governing diffusion in biological tissues. [Yongmin Zhong, Bijan Shirinzadeh, Julian Smith, Chengfan Gu, 2009] proposes an improved reaction–diffusion model (which is an electromechanical based deformable model) to describe the distribution of the mechanical load in soft tissues, and a three-layer artificial cellular neural network is used to solve the reaction–diffusion model for real-time simulation of soft tissue deformation. The proposed model can accommodate isotropic, anisotropic and inhomogeneous deformations just by modifying diffusion coefficients.

[Y. Ng, C. Song, D. McLean, S. M. Shimi, T. G. Frank, A. Cuschieri, 2003] develops a suture analogue that is suitable for surgery that uses staple constructed from NiTi shape memory alloy (SMA). The staple is closed by resistive heating via a pulse of electrical current. High-resolution thermal imaging is used to observe the dynamic temperature distributions in SMA staples as a function of the pulse parameters. The data obtained can be used to validate computational finite-element models of the heat transport phenomena. Heat sink effect of the electrical contact rails as well as the presence of contact hotspots are considered so that deployment protocols are optimized and thermal collateral damage to tissue is minimized. [Javad Dargahi, Siamak Najarian, Bin Liu, 2007] deals with the sensitivity analysis (both experimental and theoretical) of a novel tactile probe for measurement of tissue softness with applications in robotic surgery. [Safdar N. Khan, Joseph M. Lane, 2004] gives an account of animal models for tissue-engineered bone constructs, as applied to spinal fusion surgery. [Jacob Rosen, Blake Hannaford, Christina G. Richards, Mika N. Sinanan, 2001] develops and assess a skill scale using Markov models (MMs). The skill scale can be used to evaluate surgeons or surgical simulators. The Markov

Modeling that is employed to model the minimally invasive surgery uses tool/tissue interaction and force/torque signatures.

[James T. Hing, Ari D. Brooks, Jaydev P. Desai, 2007] presents a methodology for modeling the needle and soft-tissue interaction during needle insertion. A biplanar fluoroscopic approach is used for the measurement, modeling, and simulation. [M.A.F. Rodrigues, D.F. Gillies, P. Charters, 1998] deals with modelling and simulation of the tongue during laryngoscopy. [Kim V. Hansen, Lars Brix, Christian F. Pedersen, Jens P. Haase, Ole V. Larsen, 2004] models the interaction between a spatula and a human brain. The aim is to provide surgeons with a tool that can teach them the correlation between deformation and applied force. Here, a finite element based model of the brain is utilized in a Virtual Reality setup. [R. Sierra, M. Bajka, G. Szekely, 2006] investigates different methods for the generation of tumor models suitable for surgical training simulators, hysteroscopy simulator in particular. A cellular automaton and a particle based tumor growth model are looked into. [Jia-Quan Wang, Yan-Jun Zeng, X-Y Li] assesses the role of the four major operational variables in the radial keratotomy operation (RK) which is performed to correct myopic eyes. The reference also studies the deformation of the cornea after the operation and it attempts to provide some valuable references for clinical practice. The finite element method is used during simulations.

[M.E.H. Eltaib, J.R. Hewit, 2003] is a review paper that reviews artificial tactile sensing systems for minimal access surgery (MAS). The technology is addressed from different viewpoints like tactile sensing, tactile data processing, and tactile display. The review paper assumes importance because restoring tactile capability to MAS surgeons (since the “sense of feel” that is used routinely in open surgery is lost in MAS) by artificial means brings immense benefits in patient welfare and safety. [Cagatay Basdogan, Suvranu De, Jung Kim, Manivannan Muniyandi, Hyun Kim, Mandayam A. Srinivasan, 2004] discusses main aspects of haptics in minimally invasive surgical simulation and training, like haptic rendering, haptic recording, and haptic playback.

[Jung Kim, Mandayam A. Srinivasan, 2005] characterizes the nonlinear viscoelastic properties of intra-abdominal organs using the data from in vivo animal experiments and an inverse FE parameter estimation algorithm. While assuming quasi-linear-viscoelastic theory, the reference estimates the viscoelastic and hyerelastic material parameters to provide a physically based simulation of tissue deformations. The reference also reports that one can successfully reduce the time and computational resources by decoupling the viscoelastic part and nonlinear elastic part in the tissue model. [Jung Kim, Bummo Ahn, Suvranu De, Mandayam A. Srinivasan, 2008] assumes that the soft tissues obey quasi-linear-viscoelastic theory, and the material parameters are estimated using an inverse FE parameter estimation algorithm. An approach that decouples the viscoelastic part and the nonlinear elastic part in a tissue model is also used to improve the performance of computations.

[Karol Miller, Kiyoyuki Chinzei, Girma Orssengo, Piotr Bednarz, 2000] reports the in-vivo mechanical properties of brain tissue. The reference uses a hyper-viscoelastic constitutive model to obtain the material parameters from experimental results. [Yi Liu, Amy E. Kerdok, Robert D. Howe, 2004] applies a nonlinear hyperelastic 8-chain network constitutive law to model soft tissues undergoing large indentations. Also, a finite element model of soft tissue indentation is developed and validated using the constitutive law. The work could serve as an initial method for determining the unique material parameters of breast tissue from indentation experiments. [M. Kauer, V. Vuskovic, J. Dual, G. Szekely, M. Bajka, 2002] deals with the inverse finite element characterization of soft tissues. [Davide Valtorta, Edoardo Mazza, 2005] introduces a new method for the dynamic measurement of soft tissue viscoelastic properties; the method makes use of a torsional resonator device.

[Evren Samur, Mert Sedef, Cagatay Basdogan, Levent Avtan, Oktay Duzgun, 2005] reports the development of a robotic indenter for minimally invasive measurement of tissue properties during a laparoscopic surgery. From the experimental results, Young's modulus of pig liver is estimated to be around 15 kPa; it is also observed that pig liver shows linear viscoelastic behavior. [F.J. Carter, T.G. Frank, P.J. Davies, D. McLean, A. Cuschieri, 2001] deals with measurements and modelling of the compliance of human and porcine organs. Experiments showed that pig spleen is much more compliant than pig liver with mean elastic moduli of 0.11 and 4.0 MPa respectively. Also, it was found that the right lobe of human liver had a mean elastic modulus of about 0.27 MPa. However, it was found that a single case of a diseased liver had a mean modulus of 0.74 MPa - nearly three times the stiffness. It was also found that an exponential stress-strain law could accurately fit uniform stress test data and that subsequent finite element modelling for non-uniform stress around a small indentor matched measured force characteristics.

[Karol Miller, 1999] proposes a large deformation linear viscoelastic model that is suitable for direct use with commercially available finite element software packages like ABAQUS. The proposed constitutive equation is of polynomial form with time-dependent coefficients; the model requires four material constants. [Karol Miller, Kiyoyuki Chinzei, 2002] contains experimental results of in-vitro uniaxial tensile test of swine brain tissue in finite deformation; it also proposes a new hyper-viscoelastic constitutive model for the brain tissue.

[Amy E. Kerdok, Simona Socrate, Robert D. Howe, 2004] presents preliminary results from large strain creep tests carried out on ex-vivo whole liver, using a perfusion system that mimics in vivo conditions; a description of the proposed constitutive model is also presented. [Alessandro Nava, Edoardo Mazza, Oliver Haefner, Michael Bajka, 2004] presents experiments on soft tissues that show the evolution of the mechanical response during a series of loading and unloading cycles. [Ahn B., Kim J., 2010] records the surface deformation and force response of porcine livers undergoing large deformations through indentation experiments, using a three-dimensional (3D) optical system and a force transducer. An inverse FEM optimization algorithm is used to estimate the model parameters assuming hyperelastic and linear viscoelastic material behavior.

Now a few theses that fall on the topics that are related to the topic of the present paper are mentioned here. [Andrew Crossan, 2003] is a Ph.D. thesis dealing with the design and evaluation of a haptic veterinary palpation training simulator. [Jesper Mosegaard, 2004] is a thesis that deals with realtime surgical simulation within the domain of congenital heart diseases. [Han-Wen Nienhuys, 2003] is a thesis dealing with cutting of deformable objects.

[Anderson Maciel, 2005] is a Ph.D. thesis that deals with a biomechanics-based articulation model for medical applications. [Jochen Lang, 2001] develops a robotic system for recording the deformation of an object that is subjected to external forces and for coming up with a model of the deformation from the recorded deformation. [Zhaochun Yang, 2004] develops a poroviscoelastic dynamic finite element model that can describe biological tissues.

[Teeranoot Chanthasopeephan, 2006] is a Ph.D. thesis experimentally obtains the force-displacement data during the cutting of a pig liver, and characterizes the soft tissue, with the intention of achieving the realistic and realtime haptic simulation of the soft tissue. [Amy Elizabeth Kerdok, 2006] develops a realistic and physically-based constitutive model for a pig liver. Finite deformations (~30% nominal strain) are considered. The thesis identifies the material parameters of the constitutive model also. [Martin Kauer, 2001] deals with the characterization of soft tissues through the inverse finite element method and aspiration experiments. A pig kidney (for ex-vivo experiments) and human uteri (for in-vivo and ex-vivo experiments) are the organs considered. Hyperelasticity and quasi-linear viscoelasticity are assumed.

Now a few books that could be of help while working on a topic related to the present paper are mentioned here. [Rudra Pratap, 2010] is an introduction to MATLAB. [Smith I. M., 1995] is a book on Fortran 90. [Alastair McKinstry, Alin Elena, Ruairi Nestor] is a just eleven page introduction to Fortran, but it covers most of the commonly used features of the language. [Blaise Barney] provides a working knowledge of the Message Passing Interface (MPI).

[Srinath L. S., 2003] is a book on solid mechanics. [Warren C. Young, Richard G. Budynas, 2002] gives formulae for stress and strain. [Lingaiah K., 1984], [Mahadevan K., Balaveera Reddy K., 2000] are the handbooks and contain data useful for mechanical design, including formulae for stress, strain, deflection etc.

[Allan F. Bower, 2009] gives a very practical explanation of solid mechanics, continuum mechanics, and the Finite Element Method. [Lawrence E. Malvern, 1969], [Truesdell C., Noll W., 2004], [Antonio Romano, Renato Lancellotta, Addolorata Marasco, 2006] are some of the books on continuum mechanics.

[Ang W. T., 2007], [Gernot Beer, Ian Moffat Smith, Christian Duenser, 2008], [Brebbia C. A., 1978], [Brebbia C. A., Dominguez J.] are some of the books that deal with the Boundary Element Method. [Alok Sutradhar, Glaucio H. Paulino, Leonard J. Gray, 2008] deals with Symmetric Galerkin Boundary Element Method which is one of the many types of the Boundary Element Method. [Youssef F. Rashed] is a beautiful tutorial on the Boundary Element Method.

[Fung Y. C., 2004] deals with the mechanical properties of different tissues. It provides mechanical models that represent the behavior of different tissues, and based on experimental results, it provides the values of different constants in these models also.

Summary

This paper lists some references that could in some way be relevant in the context of the real-time computational simulation of biological organs, the research area being defined in a very broad sense.

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