Cognition-guided Surgery
or
How to Integrate Surgical Expert Knowledge into an HPC-based FEM Surgery Simulation?

N. Schoch[1], S. Engelhardt[2], N. Zimmermann[3], S. Speidel[4], R. De Simone[3], I. Wolf[2], and V. Heuveline[1]

Abstract: Medical simulations more and more play an important role in today's clinical and surgical treatment processes. They not only can contribute to the overall understanding of human physiology, but also enhance diagnosis tools, give additional information for risk analysis and hence allow for optimal surgery planning.

We specifically look at the surgical operation of a mitral valve reconstruction (MVR), which re-establishes the functionality of incompetent mitral valves by applying surgical techniques. Surgical expert knowledge and experience is crucial for a successful operation, where an artificial annulus ring is implanted into the heart in order to reshape its geometry. Biomechanical soft tissue simulations of appropriate MVR operation scenarios can support surgeons in their decision and execution process during the operation. In our work, we focus, firstly, on how such simulations can be improved by means of integrating surgical expert knowledge, and secondly, on how an efficient usage of High-Performance Computing (HPC) methods allows for obtaining the respective simulation results in almost real-time.

At first, we explain our framework for the expert knowledge-based setup of simulation scenarios for an MVR: Applying 'surgical rules' on patient-specific data, we obtain a set of distinct boundary conditions for the biomechanical simulation of a set of MVR surgery scenarios. The simulation is based on the Finite Elements Method (FEM) and implemented in the open-source C++ FEM software HiFlow^3. It allows for simulating the behaviour of the mitral valve under the effects of blood pressure and displacements imposed through the implantation of the artificial annulus ring. Secondly, we present our HPC-infrastructure-based approach to intraoperatively provide simulation results to the surgeon: On the one hand, we allow for an easy and seamless integration of the simulation into the clinic workflow by means of distributing, activating and controlling the MVR simulation scenarios via the Medical Simulation Markup Language (MSML). On the other hand, our simulation is based on highly-efficient numerical modeling algorithms and optimized with respect to hardware-aware numerics. We built up a problem-specific parallelization strategy, not only for mesh partitioning and the corresponding assembly of the FEM matrices and vectors, but also with respect to the solvers and preconditioners. The whole HPC-based setup has the potential to intraoperatively support the decision-making process during an MVR where the surgeon usually has to make fundamental decisions under time pressure.

[1] Engineering Mathematics and Computing Lab (EMCL)
Interdisciplinary Center for Scientific Computing (IWR), University of Heidelberg
Speyerer Str. 6, 69115 Heidelberg, Germany
nicolai.schoch@iwr.uni-heidelberg.de, vincent.heuveline@iwr.uni-heidelberg.de

[2] Medical and Biological Informatics (MBI), German Cancer Research Center (DKFZ)
Im Neuenheimer Feld 280, 69120 Heidelberg, Germany
sandy.engelhardt@dkfz-heidelberg.de, i.wolf@dkfz.de

[3] Cardiac Surgery, University Hospital Heidelberg
Im Neuenheimer Feld 672, 69120 Heidelberg, Germany
norbert.zimmermann@med.uni-heidelberg.de, raffaele.de.simone@med.uni-heidelberg.de

[4] Institute for Anthropomatics, Karlsruhe Institute of Technology (KIT)
Adenauerring 2, 76131 Karlsruhe, Germany
stefanie.speidel@kit.edu