2017 Computational Biomechanics for Medicine XII

- 8:00 to 10:00 sessions
  - 8:20 welcome
    - Poul Nielsen
  - 8:30 keynote 1
    - **Making head and neck reconstruction surgery an engineering process**
      - Sid Fels
      - Computer modeling and simulation of the human body is rapidly becoming a critical and central tool in a broad range of disciplines, including engineering, education, entertainment, physiology and medicine. Often, these models underpin the goal of transitioning from an artisanal practice to designing and making to an industrial engineering process. One reason for this approach is that designed and simulated models can be thoroughly tested used manufactured by machine to high tolerances, potentially removing much of the guess work when addressing complex human body dynamics and variations. The challenge for researchers is how to create patient specific models with enough fidelity for in-silico simulation to accurately predict treatment outcomes. To address these challenges, we are developing technology to create dynamic, parametric, multiscale models of human musculoskeletal anatomy that can later be extended to include organ structures and other subsystems. We are working to provide a range, from low-to-high accuracy, of models, including high-resolution bone surfaces and detailed representations of muscle fibre structure and pennation. A significant component of our approach provides 3D finite element (FEM) muscle models coupled with multibody simulation techniques including contact handling and constraints. Our primary modelling effort is for the oral, pharyngeal and laryngeal (OPAL) complex to predict functional outcomes, such as chewing, swallowing and speaking. I report on our progress with our interdisciplinary team of scientific and clinical investigators, and collaborators and iRSM partners, the advances we have made including: an advanced Functional Reference ANatomy Knowledge (FRANK) template of the head and neck that can be registered structurally and functionally to patient specific data, new techniques for patient specific registration, liquid bolus simulations in the head and neck models, and a new technique for simulating speech from the biomechanics of the airway. Based on our experiences, I will outline a number of grand challenges that require a community of clinical, scientific and engineering researchers to address before we can transition to patient treatment as an engineered solution.
  - 9:30 podium 1
    - **Atlas of acceleration-induced brain deformation from measurements in vivo**
      - Arnold D. Gomez, Andrew Knutsen, Deva Chan, Yuan-Chiao Lu, Dzung L. Pham, Philip Bayly, Jerry L. Prince
      - In traumatic brain injury (TBI), rapid head acceleration resulting from a blow or fall results in detrimental brain tissue deformation. These types of injuries are frequent and can have devastating effects. Understanding the relationship between acceleration and deformation is a challenging and essential step towards designing effective preventive strategies. This study describes patterns of acceleration-induced brain deformation in a group of human volunteers (n=7). Unlike previous research, the analysis herein involved spatiotemporal analysis of 3D kinematics. In each subject, tagged magnetic resonance imaging (MRI) was acquired during a mild acceleration event, and displacements were extracted using a mechanically regularized motion estimation algorithm. This technique involved registering an anatomical template (a finite-element mesh) to all of the subjects allowing translation of scalar strain projections back to the template to be averaged. Our results show that, in individuals, weighting acceleration measurements by the subject's brain volume improves the correlation between acceleration magnitude and deformation (of 0.66 in the weighted comparison, compared to 0.34). In individuals, and the group, brain deformation peaked after the peak acceleration, and near the interface between the brain and the skull. However, some deformation was also observed near medial brain structures, which supports the idea that the falx plays a role in transferring mechanical power to the middle of the brain.
- 10:00 to 10:30 coffee break
- 10:30 to 12:30 sessions
  - 10:30 podium 2
    - **Reconstruction of real-world car-to-pedestrian accident using computational biomechanics model: effects of the choice of boundary conditions of the brain on brain injury risk**
      - Fang Wang, Bingyu Wang, Yong Han, Qian Peng, Fan Li, Adam Wittek
      - In the current study, the effects of the approach for modelling the brain-skull interface on prediction of the brain injury risk are investigated using a previously validated computational head-brain model. Four types of brain-skull interface modelling approaches (1: the method used in original Total HUman Model for Safety THUMS Head-brain model; 2: brain rigidly attached to the skull, 3: frictionless contact between the brain and skull, and 4: cohesive layer (spring-type) between the brain and skull) are employed in numerical reconstruction of a real-world car-to-pedestrian impact accident. The results indicate that the predicted brain injury risk is strongly affected by the approach for modelling the

brain–skull interface. The comparison of the predicted risk of diffuse axonal injury DAI and brain contusions with the injuries sustained by the pedestrian involved in the accident seems to suggest that accurate prediction of the brain injury risk using computational biomechanics models requires direct representation of the meninges and subarachnoidal space with the CSF.

- 11:00 podium 3
  - **Computational modeling of fluid-structure interaction between blood flow and mitral valve**
    - Weixin Si, Xiangyun Liao, Jing Qin, Pheng Ann Heng
    - Mitral valve repair is a complex operation, in which the functionality of incompetent mitral valve is reconstructed by surgical techniques. Simulation-based surgical planning system, allowing surgeons to simulate and compare potential repair strategies, could greatly improve surgical outcomes. This paper presents a practical computational framework, combining the Total Lagrangian Explicit Dynamics Finite Element Method (TLED FEM) and Smoothed Particle Hydrodynamics (SPH), to solve the interaction problem of blood and immersed mitral valves. With this completed pipeline, we can not only predict the mechanical behavior of mitral valve, but also analyze the transvalvular pressures distributed on valve leaflets. The experimental results demonstrate that our method has the potential to be applied in surgical planning simulator of mitral valve repair.
- 11:30 podium 4
  - **Maximum principal AAA wall stress is proportional to wall thickness**
    - Karol Miller, Grand Joldes, J. Qian, A.P. Patel, M.S. Jung, A. Tavner, Adam Wittek
    - Abdominal aortic aneurysm (AAA) is a permanent and irreversible dilation of the lower region of the aorta. It is an asymptomatic condition which if left untreated can expand to the point of rupture. Mechanically-speaking, rupture of an artery occurs when the local wall stress exceeds the local wall strength. It is therefore desirable to be able to estimate the AAA wall stress for a given patient non-invasively, quickly and reliably. Recently our Intelligent Systems for Medicine Laboratory (ISML) and a group from Oregon Health and Science University have presented very efficient methods to compute AAA wall stress using geometry from CT scans, and median arterial pressure as the load. The ISML's method is embedded in the software platform BioPARR - Biomechanics based Prediction of Aneurysm Rupture Risk, freely available from http://bioparr.mech.uwa.edu.au/. Experience with over fifty patient-specific stress analyses, as well as common sense, suggests that the AAA wall stress is critically dependent on the local AAA wall thickness. This thickness is currently very difficult to measure in the clinical environment. Therefore, we conducted a simulation study to elucidate the relationship between the wall thickness and the maximum principal stress. The results of the analysis of three cases presented here unequivocally demonstrate that this relationship is approximately linear, bringing us closer to being able to compute predictive stress envelopes for every patient.
- 12:00 podium 5
  - **An immersed boundary method for detail-preserving soft tissue simulation from medical images**
    - Christoph J. Paulus, Roland Maier, Daniel Peterseim, Stéphane Cotin
    - Simulating the deformation of the human anatomy is a central element of Medical Image Computing and Computer Assisted Interventions. Such simulations play a key role in non-rigid registration, augmented reality, and several other applications. Although the Finite Element Method is widely used as a numerical approach in this area, it is often hindered by the need for an optimal meshing of the domain of interest. The derivation of meshes from imaging modalities such as CT or MRI can be cumbersome and time-consuming. In this paper we use the Immersed Boundary Method (IBM) to bridge the gap between these imaging modalities and the fast simulation of soft tissue deformation on complex shapes represented by a surface mesh directly retrieved from binary images. A high resolution surface, that can be obtained from binary images using a marching cubes approach, is embedded into a hexahedral simulation grid. The details of the surface mesh are properly taken into account in the hexahedral mesh by adapting the Mirtich integration method. In addition to not requiring a dedicated meshing approach, our method results in higher accuracy for less degrees of freedom when compared to other element types. Examples on brain deformation demonstrate the potential of our method.

- 12:30 to 13:30 lunch
  - 13:00 posters
    - **A flux-conservative finite difference scheme for the numerical solution of the nonlinear bioheat equation**
      - George C. Bourantas, Grand R. Joldes, Adam Wittek, Karol Miller
      - We present a flux-conservative finite difference (FCFD) scheme for solving the nonlinear (bio)heat transfer in living tissue. The proposed scheme deals with steep gradients in the material properties for malignant and healthy tissues. The method applies directly on the raw medical image data without the need for sophisticated image analysis algorithms to define the interface between tumour and healthy tissues.
        We extend the classical finite difference (FD) method to cases with high discontinuities in the material properties. We apply meshless kernels, widely used in Smoothed Particle Hydrodynamics (SPH) method, to approximate properties in the off-grid points introduced by the flux conservative differential operators. The meshless kernels can accurately

capture the steep gradients and provide accurate approximations. We solve the governing equations by using an explicit solver. The relatively small time-step applied is counterbalanced by the small computation effort required at each time step of the proposed scheme. The FCFD method can accurately compute the numerical solution of the bioheat equation even when noise from the image acquisition is present.
Results highlight the applicability of the method and its ability to solve tumor ablation simulations directly on the raw image data, without the need to define the interface between malignant and healthy tissues (segmentation) or meshing.

- **Quantifying carotid pulse waveforms using subpixel image registration**
  - Amir HajiRassouliha, Emily Lam Po Tang, Martyn P. Nash, Andrew J. Taberner, Poul M. F. Nielsen, Yusuf O. Cakmak
  - Cardiovascular diseases are a common cause of death. Symptoms of cardiovascular disease often arise at a stage of the disease where treatments are ineffective. Hence, methods that can help early diagnosis of heart problems are essential for preventing heart failure. Assessing the shape of the carotid artery waveforms is one of the methods that clinicians use to diagnose heart and valvular diseases, such as hypertrophic obstructive cardiomyopathy, aortic stenosis, and aortic regurgitation. The carotid artery waveforms may be estimated using pulsed-Doppler ultrasound devices, or quantified using catheterisation. However, both of these solutions have limitations. Currently, among available solutions, there is no inexpensive, non-invasive objective method, or diagnostic tool for estimating or quantifying the carotid waveforms. To address these limitations, we have designed a portable non-contact camera-based device to quantify the carotid arterial waveforms. The proposed device calculates the vessel-induced deformation of skin from videos taken from the neck to estimate the carotid artery pressure waveforms. This device takes advantage of our precise and sensitive subpixel image registration algorithm to measure skin deformations from sequential frames of the videos. The skin deformations obtained using our device were compared against a laser displacement measurement device with a resolution of 0.2 μm, and a correlation score of 0.95 was achieved for five subjects.

- **A discrete element method for modelling cell mechanics – application to the simulation of chondrocyte behavior in the growth plate**
  - Grand R. Joldes, George C. Bourantas, Adam Wittek, Karol Miller, David W. Smith, Bruce S. Gardiner
  - In this paper we describe a discrete element method (DEM) framework we have developed for modelling the mechanical behavior of cells and tissues. By using a particle method we are able to simulate mechanical phenomena involved in tissue cell biomechanics (such as extracellular matrix degradation, secretion, growth) which would be very difficult to simulate using a continuum approach.
    We use the DEM framework to study chondrocyte behavior in the growth plate. Chondrocytes have an important role in the growth of long bones. They produce cartilage on one side of the growth plate, which is gradually replaced by bone. We will model some mechanical aspects of the chondrocyte behavior during two stages of this process.
    The DEM framework can be extended by including other mechanical and chemical processes (such as cell division or chemical regulation). This will help us gain more insight into the complex phenomena governing bone growth.

- 13:30 to 15:30 sessions
  - 13:30 keynote 2
    - **Computational biomechanics modelling for image guided interventions**
      - David Hawkes
      - This talk reviews attempts to apply computational biomechanics modelling to compensate for soft tissue motion and deformations in surgical planning and image guided surgery. The presentation will concentrate on structures that deform significantly between imaging for planning and the intervention. Proposed solutions for interventions and therapies in lung, breast and prostate are described along with estimates as to their accuracy and reliability and strategies for validation in these demanding applications. Computational modelling incorporating knowledge of tissue properties potentially provides a more accurate interpolant or extrapolant to information derived from intra-procedure imaging and sensing. Challenges remain as to how these two types of information might be integrated and how recent advances in population based machine learning may be used to further constrain estimates of the location of the target and organs at risk.
  - 14:30 podium 6
    - **A comparison of biomechanical models for MRI to digital breast tomosynthesis 3D registration**
      - P. Cotič Smole, C. Kaiser, J. Krammer, N.V. Ruiter, T. Hopp
      - Increasing interest in multimodal breast cancer diagnosis has led to the development of methods for MRI to X-ray mammography registration. The severe breast deformation in X-ray mammography is often tackled by biomechanical models, yet there is no common consensus in literature about the required complexity of the deformation model and the simulation strategy. We present for the first time an automated patient-specific biomechanical model based image registration of MRI to digital breast tomosynthesis (DBT). DBT provides three-dimensional information of the compressed breast and as such drives the registration by a volume similarity metric. We compare different simulation strategies and propose a patient-specific optimization of simulation and model parameters. The average three-

dimensional breast overlap measured by Dice coefficient of DBT and registered MRI improves for four analysed subjects by including the estimation of unloaded state, simulation of gravity and a concentrated pull force that mimics manual positioning of the breast on the plates from 88.1 % for a mere compression simulation to 93.1 % when including all our proposed simulation steps, whereas additional parameter optimisation further increased the value to 94.4 %.

- 15:00 podium 7
  - **Towards a real-time full-field stereoscopic imaging system for tracking lung surface deformation under pressure controlled ventilation**
    - Samuel Richardson, Thiranja P. Babarenda Gamage, Amir HajiRassouliha, Toby Jackson, Kerry Hedges, Alys Clark, Andrew Taberner, Merryn H. Tawhai, Poul M.F. Nielsen
    - The normal decline in lung function that occurs with age is virtually indistinguishable from early disease, leading to frequent misdiagnosis in the elderly. Computational modelling promises to be a useful tool for improving our understanding of lung mechanics. However, there is currently no unified structure-function computational model that explains how age-dependent structural changes translate to decline in whole lung function. Furthermore, existing models suffer from weak parameterisation due to lack of available data. To begin addressing this issue, we have developed a real-time full-field stereoscopic imaging system for tracking surface deformation of the rat lung during pressure-controlled ventilation. The system will enable the acquisition of novel physiological data on lung tissue mechanics. This study presents preliminary lung surface tracking results from experiments on Sprague-Dawley rats under pressure controlled ventilation. This rich data will provide us with previously unavailable information for constructing and validating more realistic computational models of the lung to help us better understand the mechanisms behind decline in lung function with aging and help guide the development of new diagnostic methods to distinguish age from lung disease.

- 15:30 to 16:00 coffee break
- 16:00 to 17:30 sessions
  - 16:00 podium 8
    - Olivier Mayeur, Jean-François Witz, Pauline Lecomte-Grosbras, Michel Cosson, Mathias Brieu
    - **Patient-specific simulation: non-destructive identification method for soft tissue under large strain – Application to pelvic system**
      - This work presents a non-destructive method to assess mechanical properties of the patient-specific soft tissues of a multi-organ system under large strain. The presented application is focusing on the female pelvic cavity. Based on an experimental data bank of mechanical properties, dynamic MRI's displacement field analysis, MRI's geometrical reconstruction and FE model of the pelvic cavity, a protocol has been developed to identify the material properties of a specific patient's organs. The purpose of this paper is to tackle that issue by using an inverse Finite Element analysis. Mechanical properties of the soft tissues are optimized to obtain the MRI's observed displacement of the cervix on the FE model.
  - 16:30 podium 9
    - **Simulating platelet transport in Type-B aortic dissection**
      - Louis P. Parker, Lachlan J. Kelsey, James Mallal, Roland Hustinx, Natzi Sakalihasan, Paul E. Norman, Barry J. Doyle
      - Aortic dissection is where the medial layer of the arterial wall is separated by a tear leading to intramural bleeding. The blood forms an alternate channel of flow known as the false lumen. Thrombosis of the false lumen is common in cases of dissection as flow conditions are typically more stagnant than in the true lumen. Central to the process of thrombosis is the activation and aggregation of platelets in the blood. Therefore, the aim of this work is to simulate the transport of platelets in a case of Type-B aortic dissection in a clinically-relevant timeframe.
        We investigated a 38 year old female with Type-B aortic dissection. After reconstructing the contrast-enhanced computed tomography (CT) scans into three dimensions, we created a computational mesh of polyhedral and prism elements. We used realistic boundary conditions at the inlet and at the outlets via 3-element Windkessel models. A one-way Lagrangian method was used to model the trajectories of platelets and particles were injected for 11 seconds over 16 cardiac cycles. The total number of injected particles was 1.5M. We ran our simulations on 512 cores of the MAGNUS supercomputer at the Pawsey Supercomputing Centre.
        We observed elevated residence times of these particles in regions of both stagnant (low TAWSS) and recirculating flow (high OSI), emphasising the need to consider both TAWSS and OSI in thrombus susceptibility predictions for dissection. Tear geometry was seen to have a dominating effect on TL haemodynamics, with platelets colliding and adhering to the wall primarily around the proximal entry tears and supra-aortic branching vessels.
        The complex flow patterns support the need for computational modeling to reveal flow conditions and prognosis for Type-B aortic dissection patients. Furthermore, high-performance computing enables computationally expensive patient- specific simulations to be carried out within a clinical timescale.
  - 17:00 wrap-up
    - Poul Nielsen