Statistical models for supporting medical diagnosis, therapy and training

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A historical remark

- The holy grail of medical image analysis: automatic interpretation of radiological images
- Numerous reasons
  - huge amount of data: productivity
  - objective criteria
  - reproducibility
- Original assumption: Segmentation can be performed completely based on image data
- This is practically never true
- A radiologist always relies on prior knowledge about the problem
  - anatomy, pathology
  - image formation, tissue appearance

Integration of prior knowledge

- Classical AI approaches
  - rule-based expert systems
  - expert knowledge is too complex
- Deformable anatomical atlas
  - a generic anatomical atlas carries all relevant information
  - mapped to individual data through physical deformation
  - driven mostly by feature/intensity similarity
  - problems
    - deformation process is biological nonsense
    - perfect warping is not enough: correspondence!!
    - reflects a static (individual) anatomy

Learning from examples

- Traditional approach: pattern recognition
- Learning problem structure in high-dimensional feature spaces
  - neural networks
  - kNN classification
  - discriminant analysis
  - support vectore machines
  - random forests
- Compact characterization of the sample distribution
  - principle component analysis
  - independent component analysis

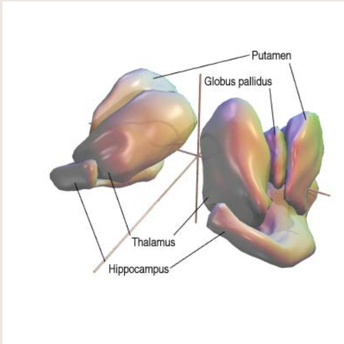
Statistical anatomical models

- Description of shape variability
- Starting from a training set of examples
  result of manual segmentation
- Generation of shape descriptor parameters
  - point distribution models
  - parametric shape models
- Normalization in anatomical coordinate system
- The variability of the anatomy is limited
  - shape variations
  - organ position
- Characterized by the distribution of the parameters
- For multivariate Gaussian
  - mean values
  - covariance (eigenvectors - modes of variation)

3D example: Basal Ganglia

- Segmentation of deep gray matter
  volumetric MRI data (gradient echo: SPGR)
- Structures to be identified
  - putamen
  - globus pallidus
  - thalamus
  - hippocampus
- Training set: 30 hand-segmented volumes
- Anatomical reference
  - midsaggital plane
  - AC/PC line
- Mean shape and first 10 eigenmodes for segmentation

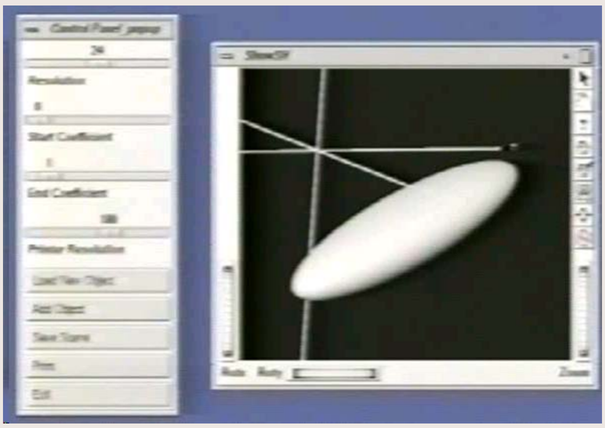
Basal Ganglia: training data



the basal ganglia
individual dataset

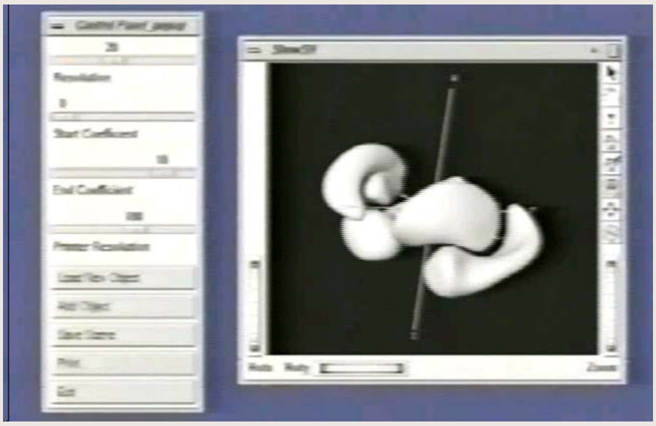
training data for left hipocampi

Basal Ganglia: shape parametrization

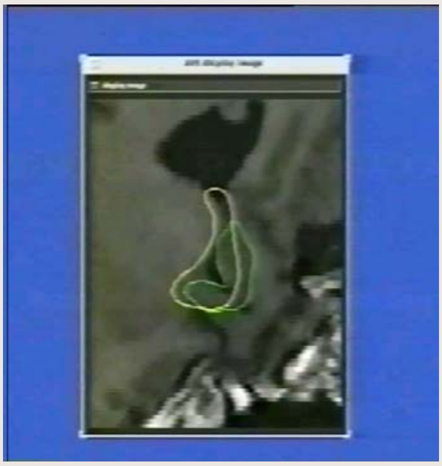


Hippocampus approximation by spherical harmonic functions

Basal Ganglia: statistical model



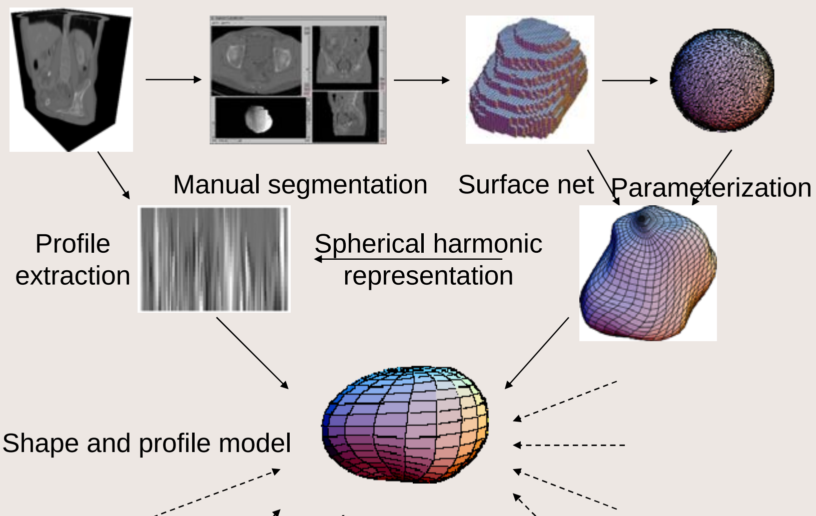
Basal Ganglia: segmentation process



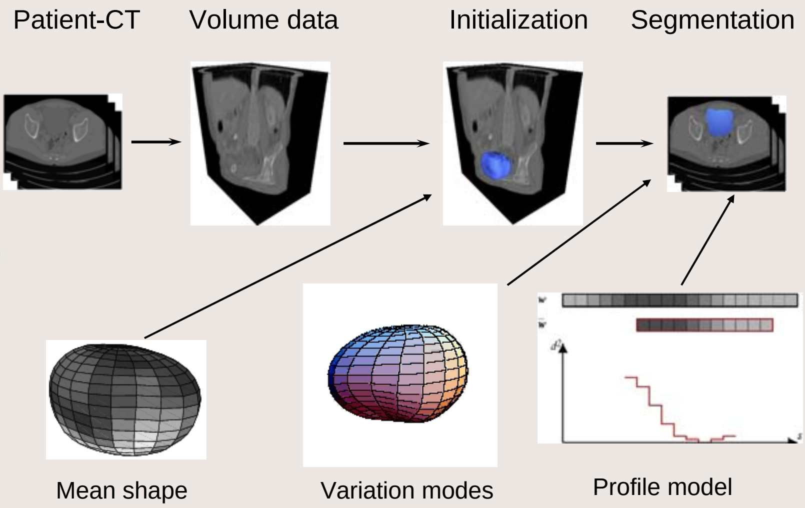
Extension of statistical models

- Knowledge about organ appearance is also essential
  e.g. characterization of gray-value profiles along organ boundaries: supports the search for optimal boundary position
- Unified framework for shape and appearance
  active appearance models
- Multi-organ models
  mutual support through inter-organ shape correlations

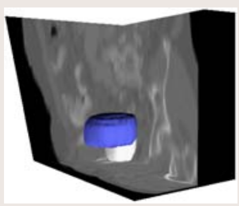
Prostate irradiation: model building

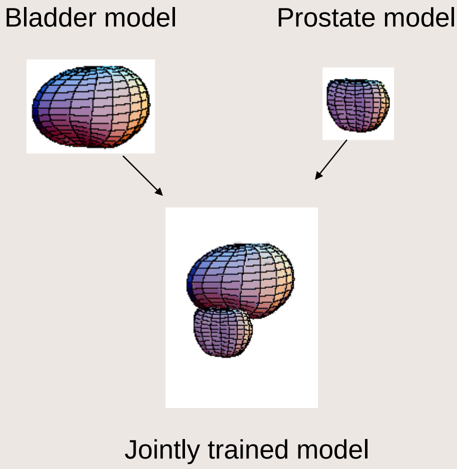


Bladder segmentation



Multi-object model

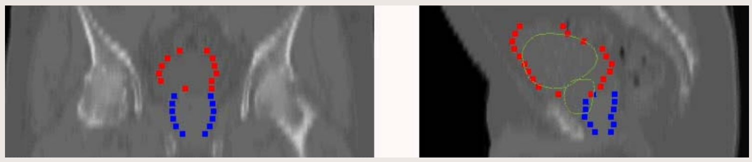




Segmentation results

Bladder: 100 Iterations

Bladder-Prostate: 50 Iterations



Problems of statistical models ...

- Establishment of inter-individual anatomical correspondence
  much progress but still an open issue
- Variability should be covered by the training set
  problems with pathology
- Less straightforward for more compex distributions
  different variants of X-component analysis (ICA)
- They cannot represent all prior knowledge

... but they are more than just regularizers

- Spatio-temporal (4D) models for motion and flow characterization
- Prediction from (very) sparse, incomplete data

Statistical models for physiology

- Anatomy „just“ describe organ geometry
- In most cases we are interested in more the functional behaviour of the body
- Physiology is inherently dynamic
- We need spatio-temporal models for characterization
- Typical examples:
  - organ motion
  - blood circulation / flow

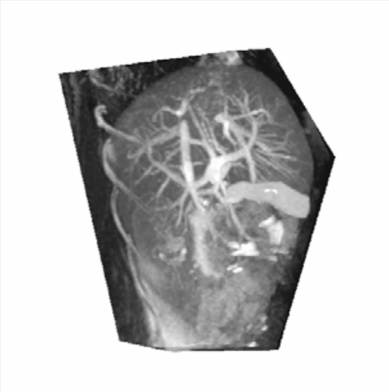
Dynamic models for clinical support

- Treatment of moving organs
  - finding pathologies during surgery or radiation therapy
  - significant motion (breathing, heartbeat)
  - shooting on moving target
- Understanding flow-related pathology formation and development
  - atherosclerosis
  - aneurysm formation

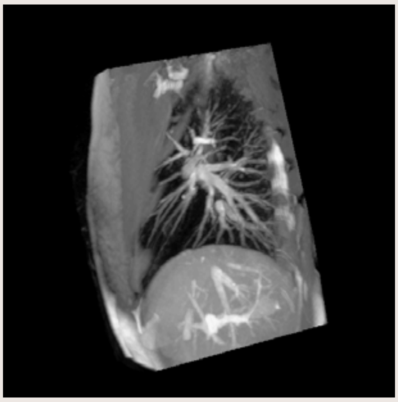
Imaging of organ motion

- Real-time
  - Optical/Photogrammetry: only surface information
  - X-ray: only 2D information
  - Ultrasound: limitations in imaging volume, resolution and image quality
- Retrospective reconstruction
  - CT, MRI: fully 4D images
  - cannot be applied during interventions
- Pathology (target) is often not visible
  implantation of fiducials can be highly invasive

MRI imaging of respiratory organ motion



liver

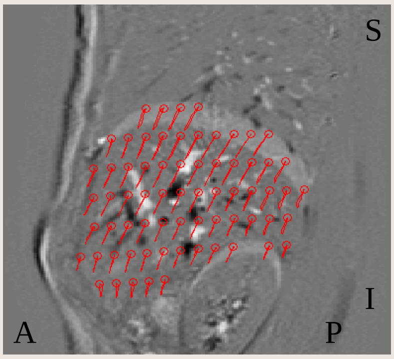


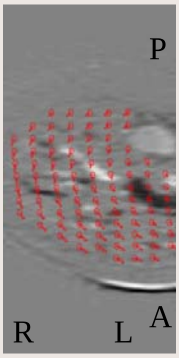
lung

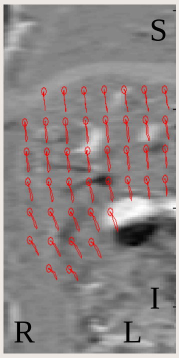
Strategy for target tracking

- Respiration is not periodic
  high variability even for a specific person
- Respiration can be observed off-line
  - individual cycles can be described as a 3D trajectory field
  - statistical models can be built from the cycles
  - even inter-individual model can be generated
    again, problem of anatomical correspondence
- No full volumetric imaging during therapy
  - observation of well identifiable predictors
  - using the statistical model to extrapolate

Liver motion trajectories



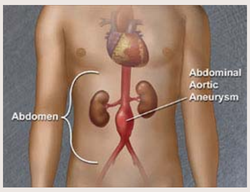


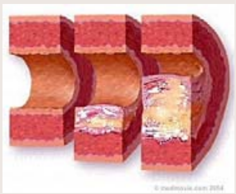


Clinical relevance of blood flow data

- Fundamental relevance in pathology formation and development
  - atherosclerosis
  - aneurysm
- Flow related information needed for
  - diagnosis
  - therapy planning
  - monitoring

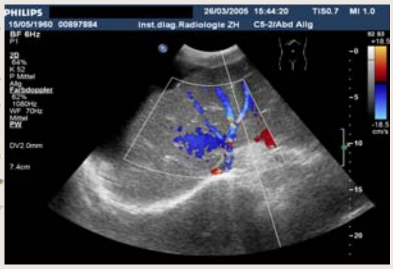
aneurysm



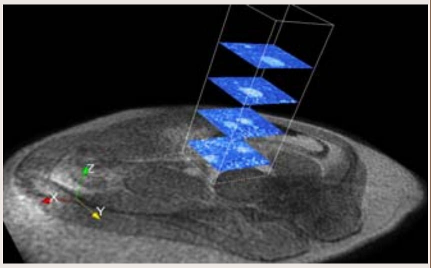


atherosclerosis

Blood flow field imaging

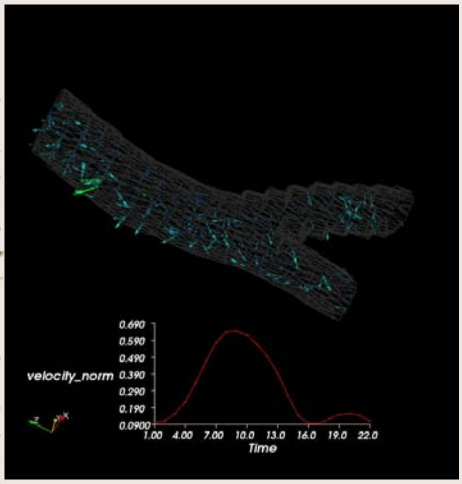


Doppler ultrasound



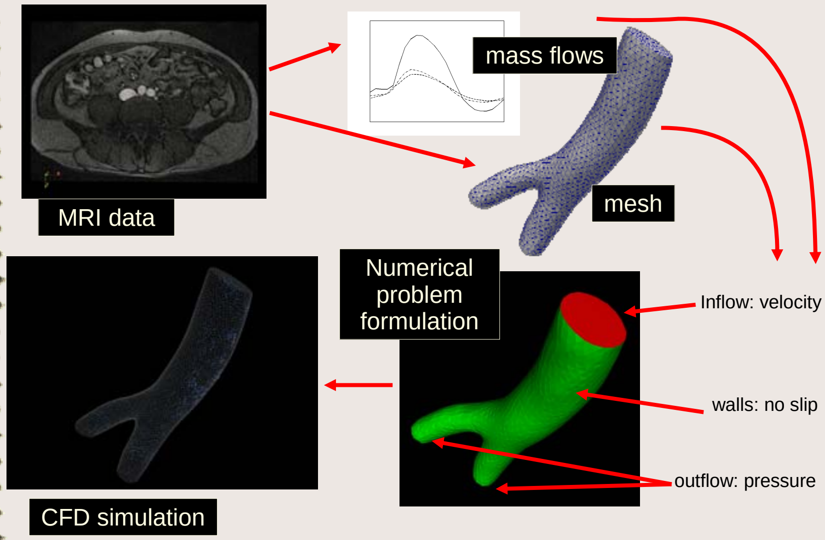
Phase contrast MRI

Measured flow information



- Spatio-temporarily resolved flow vector fields
- Problems
  - low resolution
  - bad SNR
    especially for low velocities
  - cannot reliably describe complex flow patterns

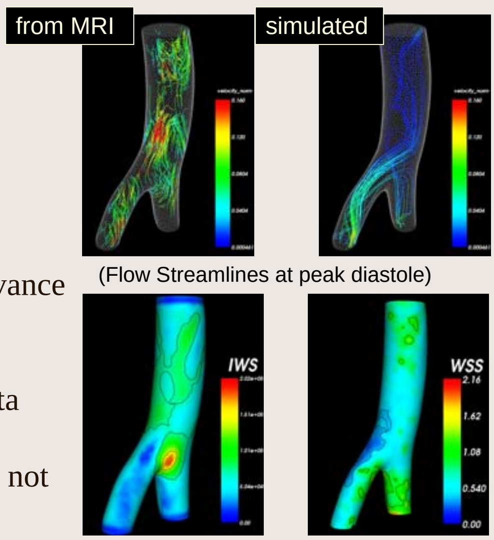
Image enhancement by simulation



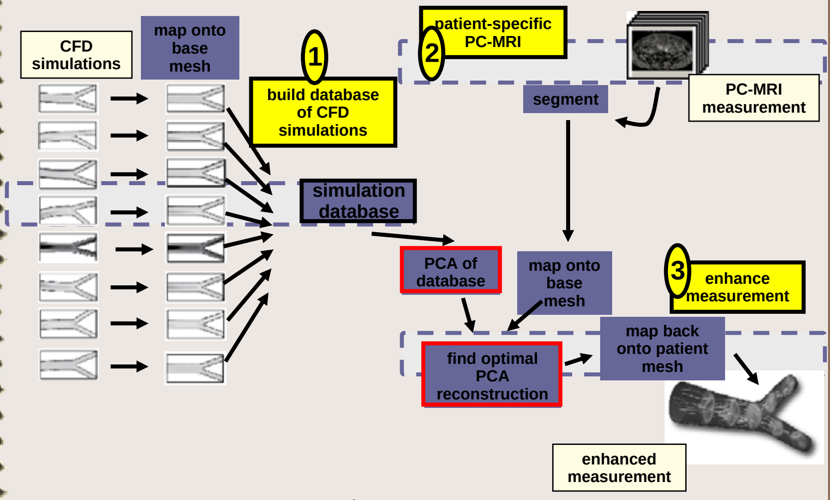
Advantages and problems

- Improved data quality
- Derivation of implicit information
  - wall stress
  - wall shear stress
  - pressure
- Major diagnostic relevance

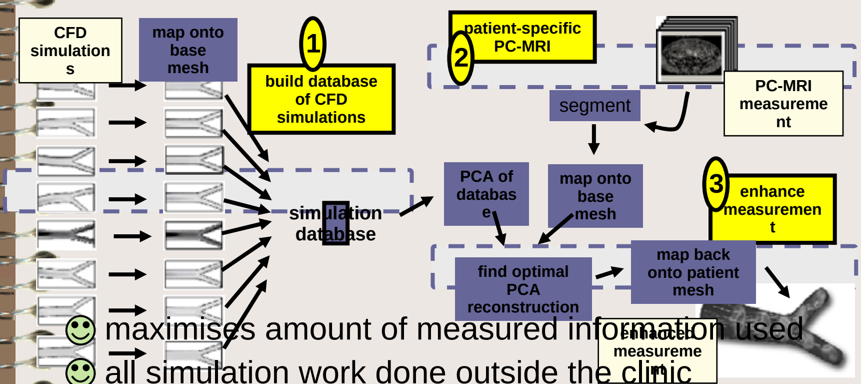
- Problems
  - most measured data discarded
  - CFD simulation is not clinically feasible



Solution: statistical flow model

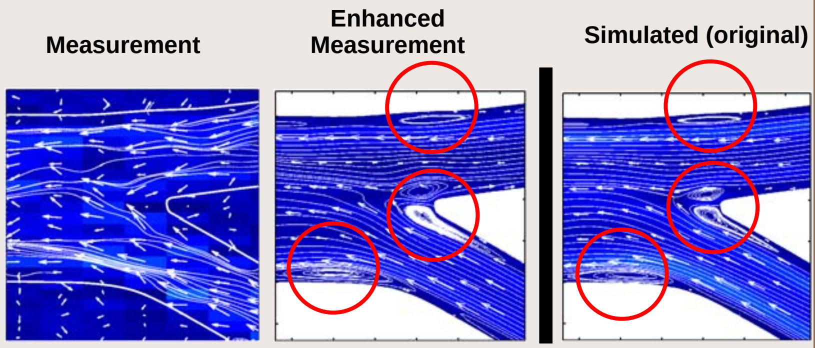


Solution: statistical flow model



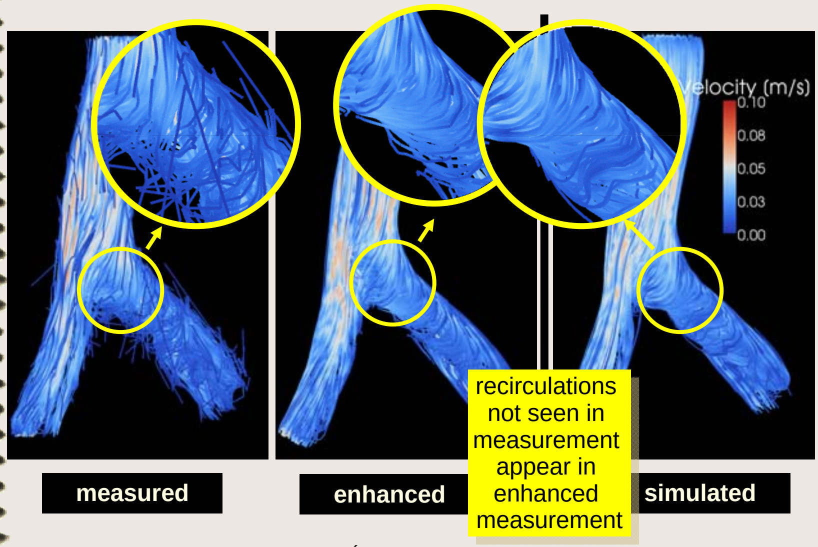
- ☺ maximises amount of measured information used
- ☺ all simulation work done outside the clinic
- ☺ clinically realistic timeframe

2D example



Recircualtion zones are well captured even though they are invisible in the measurement

3D example



Organ prediction from minimal information

Paradigm change in surgery

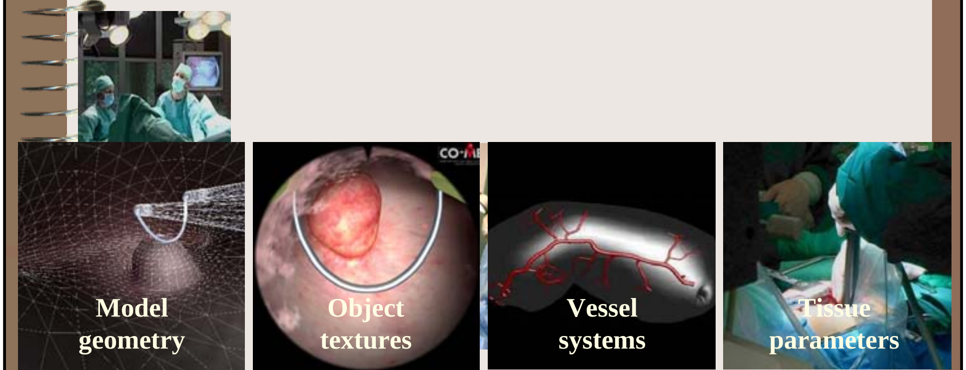
- minimally invasive procedures: endoscopy
- highly reduced damage on healthy tissue
- reduction of trauma, faster patient recovery

Training in endoscopic surgery

- Major problems for the surgeon
  - no direct access to the operation scene
  - unusual visual feedback and instrument manipulation
  - difficult to perform
- Special training necessary
  - traditionally learning on patients
  - possible replacement: virtual reality
    well established and succesful in pilot training
- Example: intra-uterine endoscopic surgery
  Hysteroscopy

Components of a surgical simulator

Components of a surgical simulator



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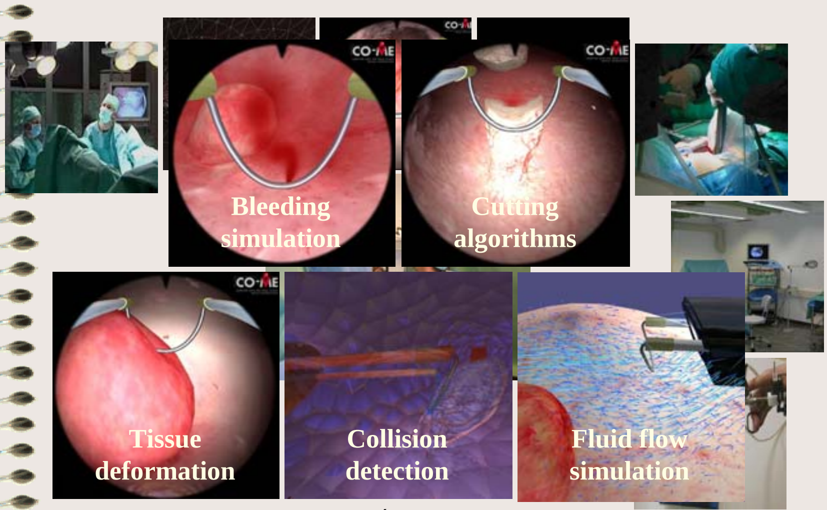
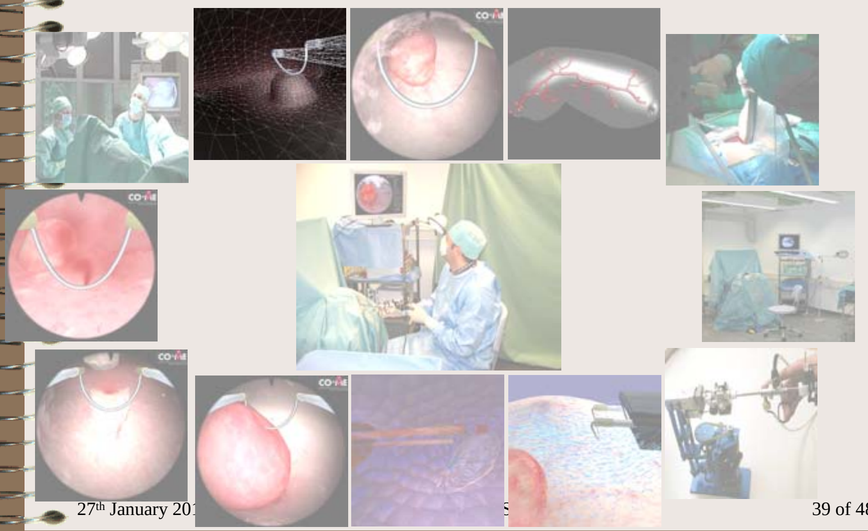
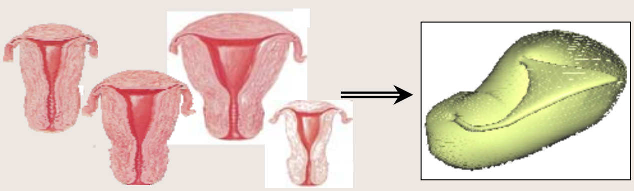


The virtual patient



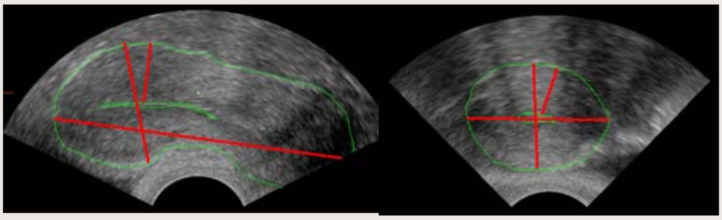
Anatomical models for training

- Usually a single (a few) pre-defined models available
- Does not allow realistic repetitive training
- Fundamental target: individual, unique anatomy for every training session
- The variability of uterus anatomy has to be coded
- Statistical shape model represents the whole population

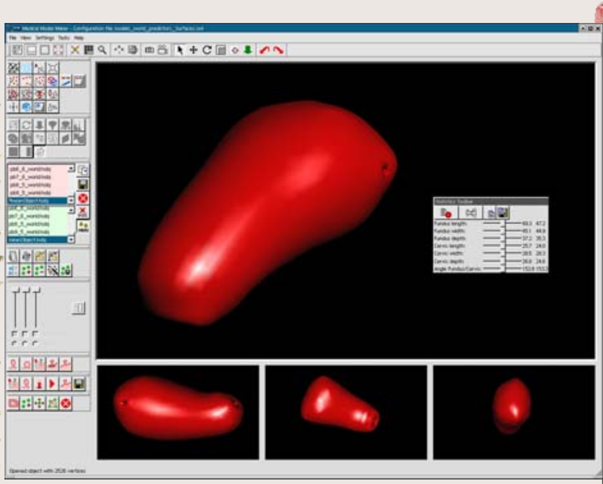


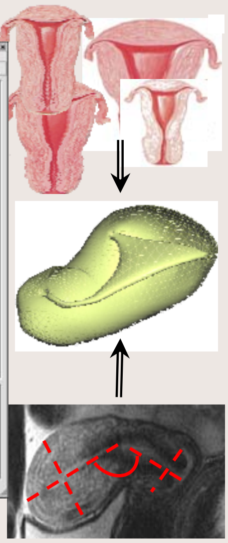
Selecting a specific example

- Fully random selection
- Can we take patient characteristics into account?
- Ultrasound diagnostics before interventions
- Characteristic measures (distances, angles,...) can be determined
- Can we draw samples respecting these measurements?
- Mathematical complication: non-linear constraints



The „uterus editor“





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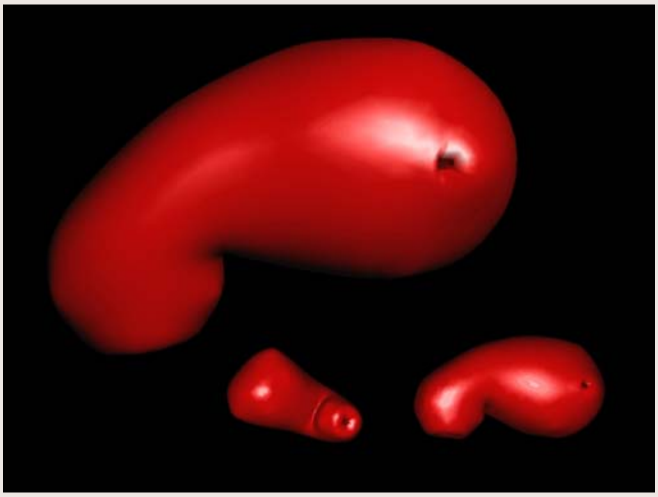
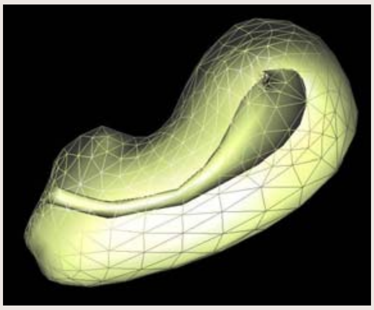


Uterus deformation

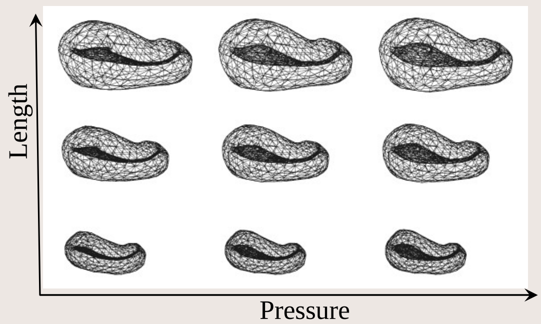
Predicting uterus expansion

- The cavity has to be expanded
- Fluid pressure is used during intervention
- Very complex, highly non-linear deformation
  - difficult biomechanical problem
  - has to be calculated in real-time



Learning biomechanics by statistical models

- Deformations can be pre-calculated off-line
- Performing for a large number of examples
- A statistical model can be built
- Intra-uterine pressure is an additional parameter can be controlled real-time



Simulated polyp removal

Summary

- Statistical models originally used for coding prior anatomical/radiological knowledge in segmentation
- Basically emulate the learning process of a radiologist
- In this context an interpolation tool
- Performance limitations
  - how representative is the training set
  - how good is the intrer-individual correspondence
- During the past decade the focus is on prediction
- The prior knowledge coded allows extrapolation from very limited information
- Very broad application domain
- Still many challenges
  - selection of optimal predictors
  - quantitative characterization: error margins