Spinal Imaging in Surgical Planning and Navigation

CSI 2015 Workshop (MICCAI 2015)
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- Software-driven medical technology (radiotherapy, surgical planning and navigation)
- Founded: 1989 in Munich
- > 1,200 employees
- > 5,000 systems // 95 countries.
Agenda / Goals

• **Main Goal**: Provide background and support ideas about using imaging and image processing procedures in spinal planning and navigation

• Basic Introduction: Spinal Planning and Navigation
  – Basic technology
  – Clinical use cases & workflows
  – Challenges & opportunities

• Sample applications:
  Imaging/image processing in spinal planning and navigation
  – Influence of imaging parameters on registration procedures
  – Elastic fusion and atlas based segmentation

• Summary
Basic Introduction: Spinal Planning & Navigation
Haimerl: Spinal Imaging in Surgical Planning and Navigation – CSI 2015
Navigation Technology
Navigation Technology
Image Guided Surgery – Basic Workflow

**Imaging**
- Preop vs Intraop
- 3D vs 2D

**Planning**
- Segmentation
- Image Fusion
- Implant Planning

**Registration**
- Surface Matching
- CT-Fluoro
- Automatic Registration

**Navigation**
- Tracking
- Instruments
Spinal Navigation: Challenges & Requirements

- Technical: Safety and Effectiveness
  - Accuracy
  - Robustness & Reliability
  - Usability
  - 95% confidence interval within 3 mm i.e. overall RMSE ~ 1.5 mm

- Clinical challenges
  - Critical structures need to be avoided (may be very tiny, e.g. cervical pedicles)
  - Accuracy requirements depend on individual anatomy and clinical indication → „Use-case specific analysis“ required
  - Not only for normal anatomy but mostly for pathologies, deformities, etc.
Spinal Navigation: Indications

- Fractures
- Spondylolisthesis
- Degenerative diseases
- Osteoporosis
- Deformity (incl. Scoliosis, Ankylosing Spondylitis)
- Stenosis / nerve decompression
- Tumors

- Often combination between different indications
- Not relevant use cases
  - Pure standard diagnostic/radiology use cases
    (which is primary focus of most imaging companies)
  - Treatment of disc protrusions/prolapses
  - Radiotherapy use cases
  - Treatment by using anterior approaches
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Spinal Navigation: Procedures

- Pedicle screws
- C1/C2 transarticular screws
- SI screws
- Other screws
- Interbody fusion
- Dorsal & lateral approaches
- Cages & implants
- Discectomy
- Decompression
- Removal of spinal tumors
- Vertebroplasty/Kyphoplasty
Use Case Specific Requirements

• Technical Requirements: Safety and Effectiveness
  – Accuracy
  – Robustness & Reliability
  – Usability
  – 95% confidence interval within 3 mm
    i.e. overall RMSE ~ 1.5 mm

• Depending on use case
  – Surgical approach
    (e.g. open vs. MIS, dorsal vs. anterior)
  – Procedure step (e.g. screw placement, cage insertion, tumor resection)
  – Critical anatomical structures
    (e.g. cervical vs lumbar, pedicle vs. disc space)
  – Individual patient anatomy and pathology
  – Type/parameters of imaging
    (e.g. 2D vs 3D, CT vs MR, scan parameters)
Spinal Navigation – Error/Influence Chain

**Imaging**
- Image modality (2D x-ray, CT, MR)
- Image quality and artifacts
- Imaging parameters

**Planning**
- Segmentation accuracy
- Image fusion accuracy

**Registration**
- Matching accuracy
- Camera accuracy

**Navigation**
- Camera
- Instrument
- Targeting
- Movement
Error/Influence Chain – Rough Estimation

• Assuming independent unbiased normal distributions with identical standard deviation $\sigma = x \text{ mm}$

• Overall accuracy: $\sqrt{x^2 + x^2 + x^2 + x^2 + x^2} \text{ mm} = \sqrt{5} x \text{ mm}$

• Requirement 95% CI within 3 mm $\Rightarrow x \text{ mm} \approx \frac{3 \text{ mm}}{1.96 \sqrt{5}} \approx 0.68 \text{ mm} = \sigma$

• Segmentation results from CSI 2014 challenge (average surface distance across all proposed methods)
  – Vertebral body: 0.494 mm
  – Left transverse process: 0.696 mm
  – Right transverse process: 0.685 mm
  – Spinous process: 0.830 mm
  – Pedicles: ?? mm
Statistical Modelling of RMS Errors

- Assuming normal distributions in all coordinates
- May be unbiased, may have different variation
- Yields Chi(3)/Maxwell distribution

- 95% confidence interval is roughly estimated by $1.96 \times \text{RMS}$ (if no substantial bias)
- Monte-Carlo-Simulation in R to calculate 95% confidence interval in more detail (based on bias value and variation)

- Comparison between RMS estimation (w/o bias) and Monte-Carlo simulation (including bias)
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Spinal Navigation – Opportunities

• Accepted Benefits
  – Higher accuracy of screw/implant placement
  – Lower radiation for patient (sometimes unclear)
  – Lower radiation for surgeons
  – Better visualization of structures

• Not fully proven, but supposed to be beneficial
  – Better clinical outcome → missing link to evaluation in terms of big data
  – Lower complication rate
  – Enabling more complex/less invasive procedures

• Further Opportunities
  – Availability of multimodal image information → Image Fusion
  – Integration of anatomical knowledge → Segmentation
  – Improved usability and reliability → Use-case specific adaptation
Influence of Imaging Parameters on Image Registration

Sample application #1
Imaging in Spinal Navigation

• 2D X-ray
  – Preoperative planning based on standing x-rays
  – 2D C-arms used as a standard for intraoperative checks
  – Navigation: Fluoro 2D based navigation / CT-Fluoro matching

• CT
  – Either pre- or intraoperative (also Fluoro 3D/Cone Beam CTs)
  – Highest geometric accuracy
  – Easier segmentation based on HU values (only for CT, not for Fluoro 3D)
  – Algorithms may depend on reconstruction kernels (soft tissue vs. bone)
  – Radiation for the patient (sometimes extra scan for navigation)

• MRI
  – Available for most of cases/indications
  –Basically for assessing soft tissue structures
  – Usually low slice resolution (depends on orientation / MR sequence)
  – Geometric distortions, noise & artifacts
Imaging in Spinal Navigation

• General Challenges
  – Navigation needs absolute accuracy, diagnostics only relative accuracy
  – Limited scan area (only 3-4 levels in many cases)
  – Differences between pre- and intraop patient position
  – Imaging artifacts (e.g. implants from previous surgeries in place)

• Special challenges for intraoperative CT imaging
  – OR/navigation equipment in place → imaging artifacts
  – Limited time for image processing algorithms
  – Preferably low dose CT scan protocols:
    no diagnostic quality / only for checking implant positions
Registration in Spinal Navigation

- Fusion between 3D data sets
  - Rigid vs elastic fusion
  - CT-MR, CT-CT, CT-Fluoro 3D, MR-Fluoro 3D?
  - Fusion with atlas → atlas-based segmentation

- Registration of preop 3d data sets
  - 2D-3D matching (e.g. CT-fluoro)
  - Surface matching
    (basically for CT, extraction of bone surface necessary)
  - Depends on reconstruction kernel: in particular, robustness

- Registration of intraoperative data sets
  - Based on pre-calibrated scanner
  - Based on fiducials
Surface Matching for Registration of Vertebrae

- Workflow
  1) Image acquisition based on specific scan protocols
  2) Automatic selection of bone threshold
  3) Optional: manual adjustment of bone threshold (based on visual appearance of bone surface)
  4) Filtering of artifacts / noise for 3D visualization and bone contour extraction
  5) Acquisition of points on bone
  6) Matching between points and surface
Influence of Imaging Parameters on Registration

• Workflow
  1) Image acquisition based on specific scan protocols
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• Parameters influencing matching results
  – CT reconstruction kernels (e.g. soft tissue vs bone kernel)
  – Selected bone thresholds
  – Initialization/starting point for registration
  – Individual and local anatomy
  – Distribution of surface points
Influence of Imaging Parameters on Registration

• Test setup
  – Definition of important clinical landmarks (e.g. pedicle, vertebral artery)
  – CT acquisition with 2-5 different reconstruction kernels from two different scanner manufacturers (GE, Siemens)
  – Selection of vertebrae across all regions of the spine (in total, 30 vertebrae across cervical, thoracal, lumbar spine)
  – Definition of surface points in CT data sets
    • several sets
    • at bone surface as visible in slice images (to mimic intraoperative point acquisition)
  – Variation across different bone thresholds
  – Variation across various starting points
Influence of Imaging Parameters on Registration

• Evaluation of matching result
  – CT coordinates as a gold standard
  – 95% confidence intervals based on TRE (RMSE) at defined anatomical landmarks
  – Rotational deviation

• Results
  – Dependency on bone threshold, reconstruction kernel & scanner type
  – (Minor) systematic error in a-p direction
  – (Minor) variation in other directions
Influence of Imaging Parameters on Registration

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Definition of Important Anatomical Landmarks

- Two groups of landmarks
  - Highest clinical/surgical impact
  - for orientational alignment

- Depends on vertebral level
  - e.g. lumbar vs cervical
  - Specific vertebrae (e.g. dens at C2, specific anatomy of C1 and sacrum)

- Defines important areas for validation
  - Could/should be included in validation of algorithms (e.g. segmentation)
  - Vertebral body (with largest area) is less important than pedicles (with substantially less area)
Robustness & Reliability of Landmark Definition

- **Purely rigid domain**
  - Comparison to a gold standard purely related by rigid transformation
  - Evaluation of TRE at defined landmarks
  - Low impact of landmark definition
  - Applicable only when only referring to rigid transformations

- **Elastic domain**
  - Validation of elastic transformations / deformable models
  - e.g. elastic fusion & atlas based segmentation
  - High impact of landmark definition
    - Limited accuracy of definition
    - 1:1 impact on evaluation
Elastic Fusion & Atlas-Based Segmentation
Sample application #2
Elastic Fusion: Basic Options

• Elastic fusion between different imaging modalities
  – Different postures between different scans and/or introp position (e.g. supine vs prone)
  – MR vs pre or intraop CT
  – Preop CT vs intraop CT

• Overcomes pure local alignment
  – Compensates differences between scan postures
  – Compensates instabilities, fractures, etc.

• Types of elastic fusion
  – Locally rigid / “multi-rigid“ (level-by-level) with extrapolation
  – Fully elastic
    (needs to stay rigid within vertebra)
  – Elastic fusion to an atlas
    → atlas based segmentation
Elastic Fusion: Requirements & Challenges

- **Validation**
  - Locally rigid domain / "multirigid"
    - rigid validation approach applicable (within bony structures)
    - Comparison to gold standard: rigid fusion on one level (already established in the field)
  - Fully elastic fusion (incl. atlas-based segmentation)
    - direct comparison between landmarks/regions
    - intra- & interobserver variability

- **Further challenges**
  - Performance in intraoperative cases
  - Between-slice resolution for MR very limited
  - Needs to work for pathologic cases in a reliable way
Atlas-Based Segmentation

• Universal atlas: Atlas containing detailed tissue information for creating virtual image data sets
  – Elastic fusion between universal atlas and patient data set
  – Transfer tissue and landmark information from atlas to individual patient data set
  – Transfer anatomical information / “normalize“ patient anatomy
Using Anatomical Knowledge – Basic Options

• Identification of basic anatomical structures
  – Bony structures (e.g. vertebral levels, pedicles)
  – Maybe also soft tissue structures (e.g. nerve roots)
  – Basic bony landmarks (e.g. entry points, basic reference points for providing local coordinates)
  – Standardized orientations (e.g. vertebral alignment)

• Optimization of usability for planning and navigation steps
  – Focus and alignment of views for specific navigation/planning tasks
  – Initialization of planning steps (e.g. implants & screws)
  – Combining background information about anatomy and clinical procedure in a use-case specific way
Using Anatomical Knowledge – Use-Case Specific

• Use-case specific analysis of safety and effectiveness
  – Reliability of reference landmarks, e.g. entry points, pedicles (even in non-navigated surgical cases)
  – Variability of risk structures and surgical areas, e.g. warnings about abnormal/small pedicles
  – Case-specific analysis of accuracy, depending on risk-likelihood relationship

• Area specific adaptation of image processing procedures
  – Risk-related weighting of areas within image segmentation procedures
  – Incorporating anatomical knowledge into image processing algorithms
  – Use-case specific adaptation of image processing algorithms
Using Anatomical Knowledge – Further Options

- Interindividual variation of anatomical structures
  - Assessment of anatomical variation in relation to normalized anatomical alignment
  - Pathology detection as comparison with normalized structures

- Support clinical procedures and their evaluation
  - Big data for evaluation of spinal procedures
  - Follow-up analysis: Fusion between pre- and post-op data sets
  - Correlation with clinical results
  - Integration of biomechanical knowledge
  - Use-case specific assessment of clinical outcome in spinal surgeries
Summary
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Conclusion

• Provided basic information about spinal navigation including
  – basic use cases, challenges and opportunities
  – impact from spinal imaging and image processing
  – some specific examples

• Hopefully provided some ideas for future steps/projects
  – to improve image processing procedures
  – to address reliability and usability
  – to focus on clinical requirements
    in typical spinal applications
  – to pave the way for creating real benefit
    in clinical procedures and follow-up
THANK YOU