Computer- and Robotic-Assisted Orthopaedic Surgery

Ferdinando Rodriguez y Baena
The MIM Lab at a Glance

HAPTIC SYSTEMS
- Haptic rendering
- Collision detection
- Realism in virtual reality
- Control algorithms & stability

TRAINING SYSTEMS
- Virtual reality
- Objective performance measures
- Staged training
- Soft/hard tissue simulation

SURGICAL SYSTEMS
- Accuracy
- Safety, size and footprint
- Surgeon-system synergy
- Minimally invasive surgery

MRI SYSTEMS
- Materials, actuators and sensors
- Master/slave teleoperation
- Magnet positioning
- Patient handling

COMMON ASPECTS
- Image Acquisition
- Image Processing
- Registration
- Tracking
Lecture Overview

• **MRCAOS** at a glance

• **Overview** of important building blocks:
  – Tracking and the acquisition of positional information
  – Intra-operative registration

• **My own case study**: robot-assisted knee surgery

• **The perils of commercialization**

• **Some conclusions** and a glimpse into the future
Technology in Orthopaedics

MORE OF AN ART THAN A SCIENCE?

Computer Aided Surgery

Computers & Trackers

Conventional Surgery

www.ndigital.com
Technology in Orthopaedics

Conventional Surgery
Technology in Orthopaedics

INTRA OPERATIVELY

Conventional Surgery

www.orthosupplier.com/players/images/mahe/product.jpg

www.orthomedex.com/medicalpowertools_pricelist.html

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Technology in Orthopaedics

Conventional Surgery
Technology in Orthopaedics

MORE OF AN ART THAN A SCIENCE?

Conventional Surgery
Technology in Orthopaedics

www.brainlab.com

www.ndigital.com
Computer Aided Surgery

- CAS systems in orthopaedics
  - BrainLab GmbH Hip & Knee Navigation
  - B-Brown’s Orthopilot™
  - Stryker Navigation™
  - Medtronic StealthStation S7™
  - BIOMET3i™ Navigator®
  - Zimmer’s ORTHOsoft® family
  - Etc.
Technology in Orthopaedics

Robotic Assisted Surgery

Computer Aided Surgery

Robotic Systems

Computers & Trackers

Conventional Surgery
Robotic Assisted Surgery

• CAS system
  – Guidance
  – Visual feed-back
  – Planning

• Intra-operative robotic system
  – Accurate and precise execution
  – Safe and reliable
  – Quicker more efficient surgery
  – Potential for a minimally invasive approach
Commercial Robots

MAZOR Bone Mounted Robot
(www.mazorrobotics.com/)

ROBODOC
(www.robodoc.com)

NavioPFS®
(www.bluebelttech.com)

RIO®
(www.makosurgical.com/)

iBlock®
(www.omnils.com)

COOPERATIVE

ACTIVE

PASSIVE
The Building Blocks of MRCAOS

**PRE-OPERATIVE**
- 2. Registration
- Pre-Operative Planning

**INTRA-OPERATIVE**
- Intra-Operative System
- 1. Tracking
- Patient Tracking & Immobilisation

**POST-OPERATIVE**
- 3. Assessment
- Post-Operative Assessment
Position Tracking
Why Track?

• Position recognition systems (trackers) are key to any CAOS application
  – Tracking of the patient (individual limbs)
  – Tracking of the instrumentation
  – Measurement system
  – To interact with the GUI

• A key link between the system and the real world
The Idyllic System

- Far-reaching
- Non-obtrusive
- Compact
- Robust
- Flexible
- Accurate

Transparent tracking!
IR-Based Trackers

• Pros
  ✓ Moderately intrusive
  ✓ Far reaching
  ✓ Many tracked objects
  ✓ High accuracy

VectorVision® (www.brainlab.com)
Optotrack Certus® (www.ndi.com)
Optotrack Certus® working envelope
IR-Based Trackers

• Pros
  ✓ Moderately intrusive
  ✓ Far reaching
  ✓ Many tracked objects
  ✓ High accuracy

• Cons
  ✗ Invasive sensors
  ✗ Line of sight
  ✗ High disposables cost
  ✗ Robust?
  • Markers motion
  • Accuracy degradation
Mechanical Tracking

• Pros
  ✓ Compact
  ✓ Very accurate
  ✓ Robust
  ✓ Intuitive

• Cons
  ✗ Small working envelope
  ✗ Physical limit to number of tracked objects
  ✗ Intrusive

Microscribe G2LX®
(www.immersion.com)

Acrobot Navigation®
(www.acrobot.ac.uk)
Electromagnetic Tracking

• Pros
  ✓ Transparent function
  ✓ Tiny sensors
  ✓ Compact

Aurora®
(www.ndi.com)

Nest of Birds
(www.ascension-tech.com)

Aurora® embedded sensors
Electromagnetic Tracking

• Pros
  ✓ Transparent function
  ✓ Tiny sensors
  ✓ Compact

• Cons
  ✗ Small working envelope
  ✗ EM Interference
  ✗ Wired connections
  ✗ High disposables cost
Digital Camera Tracking

• Pros
  ✓ Full immersion
  ✓ Flexible
  ✓ Cheap

MicronTracker2® DuraMarks
Digital Camera Tracking

- **Pros**
  - ✓ Full immersion
  - ✓ Flexible
  - ✓ Cheap

- **Cons**
  - ✗ Line of sight
  - ✗ Poor depth resolution
  - ✗ Limited workspace
  - ✗ Long warm-up time (~15 min)

*MicronTracker2® working envelope*
# Trackers at a Glance

<table>
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<th>Mechanical</th>
<th>Magnetic</th>
<th>Optical</th>
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<td>Compactness</td>
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<td>Poor depth resolution</td>
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<td>Warm-up time</td>
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Intra-Operative Registration
What is Registration

- e.g. Patient Model
- e.g. Real Patient

- Target
- Digitised landmark
- Digitising accuracy
What is Registration
What is Registration

- Target
- Digitised landmark
- Digitising accuracy

Error ↓↓
Why is Registration Important

• Defines position of patient in OR
• **Key step** in any navigated or robotic procedure
• Registration accuracy has a **direct impact** on surgical outcome
• Common cause for **procedure abortion**
• Arguably the single **most time consuming step** of a CAOS procedure
The Golden Standard

- Fiducial registration
  - Accurate
  - Repeatable
  - Reliable
  - Absolute
  - Robust
- Additional surgery to implant the markers
- Not MI compatible
- Alternative required
Registration Techniques

- Intra-operative Registration
  - Image-Free Registration
    - Geometric Methods
    - Morphing Methods
    - Image-Based Registration

INTRA-OPERATIVE MODALITIES
Image-Based - Mechanical Tracking
Image-Based - Optical Tracking

www.brainlab.com
Image-Based - Fluoroscopy

- Non-invasive modality
- Susceptible to intra-operative setup (e.g. instruments in field of view, patient orientation)
- Patient and surgeon radiation
- Cumbersome and obtrusive
Image-Based - Ultrasound

- Non-invasive landmark acquisition
- Suitable for image-based and image-free registration
- Low cost
- Accessible
- Radiation free
- Accurate enough?

http://www-sop.inria.fr/epidaure
Image-Based Registration

• Pros
  ✓ Longer track record
  ✓ Pre-operative planning
  ✓ Valuable for non standard anatomy
  ✓ Pre-operative sizing means better inventory management
  ✓ Planned vs. achieved error can be accurately assessed

• Cons
  ✗ Pre-operative imaging required
  ✗ Image processing needs to be performed by trained staff
Image-Free - Geometric Methods

- Palpated landmarks
- Digitised features
- Functional anatomy reconstruction
Image-Free - Morphing Methods

- Kinematic model derived from landmark acquisition
- Patient anatomy reconstructed from incomplete sparse data
- Actual shape is morphed from a deformable model of normal anatomy
- Accuracy degrades where anatomy has not been digitised
Image Free Registration

• Pros
  ✓ No pre-operative imaging
    (i.e. no additional radiation for the patient)
  ✓ No image processing
    (i.e. no additional radiographer time)
  ✓ No pre-operative planning
    (i.e. no additional pre-op surgeon time)

• Cons
  ❌ Localised accuracy
  ❌ Time penalty with little scope for improvement
  ❌ Non standard anatomy?
A Case Study: The Acrobot Success Story (sort of)
Imperial’s Own Experience

• “Active-constraints” robotics
  – Force-controlled joystick on end of robot
  – Surgeon moves, while robot constrains within a pre-op plan
  – Surgeon judges, senses, adapts - a good synergy

• ACROBOT
  – An ACtive constraint ROBOT for minimally invasive Unicomaprtmental Knee Arthroplasty (UKA)
  – CT-based plan (so image-based) & mechanical tracking
TKR or UKR?
The ACROBOT System
Preoperative Planning

Segmentation

Prostheses Alignment

Mechanical Axis Alignment

Boundary Generation

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Constraints

FEMORAL COMPONENT

TIBIAL COMPONENT & INSERT

a) Oxford Unicompartmental Knee Implants on CT Generated Surface Models

b) Oxford Unicompartmental Femoral Component Round Cut (I), and Locating Hole (II)

c) Oxford Unicompartmental Tibial Component Flat Cut (I), and Locating Keel (II)
Intra-Operative Procedure

Intra-Operative system

Implantation

Cutting

Registration
Robotic Assisted UKA

The Acrobat Company Limited

Robotically Assisted Unicompartmental Knee Replacement Surgery
Post-Operative Assessment
Current Practice

- Short AP & lateral x-rays
- Long standing x-rays
- Soft knee scores
CT Based Assessment

1. Pre-Operative CT
CT Based Assessment

1. Pre-Operative CT
2. Post-Operative CT
3. assessment
CT Based Assessment

1. Pre-Operative CT
2. Post-Operative CT
3. Surface to surface registration
CT Based Assessment

1. Pre-Operative CT
2. Post-Operative CT
3. Surface to surface registration
4. Post-operative alignment error assessment
Robotic Uni-Condylar knee Trial

• Prospective randomised clinical trial of robot system
• Approved by MHRA
• 15 patients conventional & 13 robotic
• All had a pre-operative plan
• Professor Justin Cobb carried out all robotic cases
Clinical Evidence

The Hurdles of Commercialisation
Technology in Orthopaedics

- Conventional Surgery
- Computers & Trackers
- Robotic Systems
- BETTER SURGICAL ACCURACY (OUTCOMES?)
- HIGHER COST/COMPLEXITY
Now and Then…

- Pre-2000 version
- First full prototype
- Cadaver trials

ACADEMIC RESEARCH
GREAT OPTIMISM
Now and Then…

- 2000-2003 version
- New gross positioner
- First TKA trials
Now and Then…

MORE FUNDING…CLINICAL SUCCESS

- 2003-2007 version
- New gross positioner
  - New AC head
  - First UKA trials
Now and Then…

Sculptor™ (Acrobot ltd.)

- 2007-2011 version
- No gross positioner!
- New Remote Centre Mechanism
- First commercial UKA prototype

Dynamic Limb Tracking

Remote Centre Mechanism

HARDWARE STREAMLINED → ALBIET NO REVENUE!
Now and Then...

- 2012 version
- New owner Stanmore Implants Worldwide
  - New body frame
  - New graphical front end
- First commercial UKA system

FIRST MAJOR ACQUISITION ➔ EXCITING OUTLOOK

Remote Centre Mechanism (RCM)

3DOF ROBOT + RCM
Now and Then…

“Savile Row™” System:

- Customised planning, manufacture and implantation…
Now and Then…

- 2013 version?
- Yet another owner *Mako Surgical inc.*
- + patient-specific implants
  + bespoke planning
  + robotic delivery
  + larger market share

SECOND MAJOR ACQUISITION ➔ CRITICAL MASS REACHED?
Now and Then...

Recent $1.65B acquisition from Stryker looks promising...will the others follow suit or just wait and see?

- 2013 version?
- Yet another owner Mako Surgical inc.
- + patient-specific implants
- + bespoke planning
- + robotic delivery
- + larger market share

SECOND MAJOR ACQUISITION ➔ CRITICAL MASS REACHED?
Conclusion
Does MRCAOS Make a Difference?

• Surgical outcome is definitely better
• Long term clinical outcome, not so clear…
  – Clear push vs. pull strategy - a historical legacy
• The technology is mature, but a stronger evidence base is needed for widespread adoption
  – Clear cost justification (lease, cons., recovery, etc.)
  – Similar or better skin to skin times
OR
  – More advanced capabilities/harder procedures
  – Better clinical justification: surgical vs. clinical outcome
Patient Specific Instrumentation

- similar skin to skin times
- patient specific approach
- comparatively cheaper
- questionable accuracy
- large surgical access
- limited range of shape cuts

→ Doubtful long-term future?
A Glimpse into the Future (with some bias...)

Better Measurement Tools

Personalised web-based tools

*e.g.* Cobb et al.

New sensing for diagnostics & assessment

*e.g.* Nathwani et al.

Modelling and simulation

*e.g.* Hopkins et al.

Pictures courtesy of

*Dr Andrew Hopkins, Zimmer Orthopaedics*
Better Technology Integration

Courtesy of Dräger Medical AG & Co. KG
Hands-On Systems & Natural Motion

- There are many benefits to hands-on robotic surgery
- However, the surgeon must also interact with the end effector dynamics
- Redundant robots can achieve a pose in an infinite number of ways
Hands-On Systems & Natural Motion

- Null-space optimization creates a more natural feeling without affecting the surgeon’s pose
- End effector mass and friction optimization demonstrated on the Kuka LWR 4+
Hands-On Systems & Natural Motion

Petersen and Rodriguez y Baena “Mass and Inertia Optimization for Natural Motion in Hands-On Robotic Surgery” (IROS 2014)
Hands-On Systems & Natural Motion

Petersen and Rodriguez y Baena “Mass and Inertia Optimization for Natural Motion in Hands-On Robotic Surgery” (IROS 2014)
Active Constraints/Virtual Fixtures

Bowyer and Rodriguez y Baena ‘Active constraints in unstructured environments’
(Workshop on cooperative control, Hamlyn Symposium 2013)
Future Trends

Active constraints
(Rigid, structured environments)

Dynamic active constraints
(Deformable, unstructured environments)
The Hidden Problem behind ACs

ACTIVE FORCING OF THE TOOL
Dynamic Frictional Constraints

https://fatsmokermma.files.wordpress.com/2013/01/judo-kevin-murphy.jpg
Dynamic Frictional Constraints

Bowyer and Rodriguez y Baena “Dynamic frictional constraints for robot assisted surgery” (World Haptics 2013)

Bowyer and Rodriguez y Baena “Dynamic frictional constraints in rotation and translation” (ICRA 2014)
A Glimpse into the Future of ACs?
People & Sponsors

**PhD students**
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