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4th Biennial North American Summer School on Surgical Robotics

Pittsburgh, 21-26 July 2014

Computer- and Robotic-Assisted Orthopaedic Surgery

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Imperial College, London, SW7 2AZ

The MIM Lab at a Glance

HAPTIC SYSTEMS

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

Knee Arthroscopy Training System

TRAINING SYSTEMS

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

Bone Mounted Spine Robot

Acrobot Hands-On Orthopaedic Robot

Haptic daVinci Telemanipulator

MIM

Open MRI

Patient Positioning

SURGICAL SYSTEMS

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

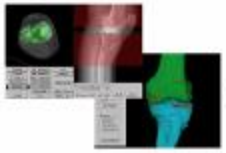
MRI-Guided Trans-Rectal Prostate Biopsy

MRI SYSTEMS

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

COMMON ASPECTS

Image Acquisition



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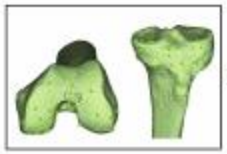

Registration

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

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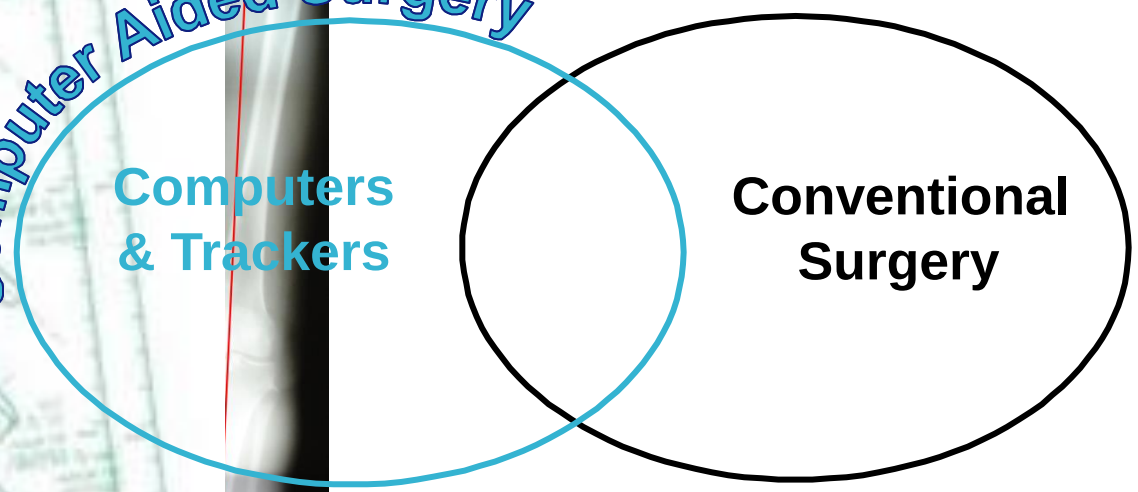
CAOS at a Glance

Technology in Orthopaedics

MORE OF AN ART THAN A SCIENCE?

www.ndigital.com



Technology in Orthopaedics

PRE OPERATIVELY

Conventional Surgery

Technology in Orthopaedics

INTRA OPERATIVELY

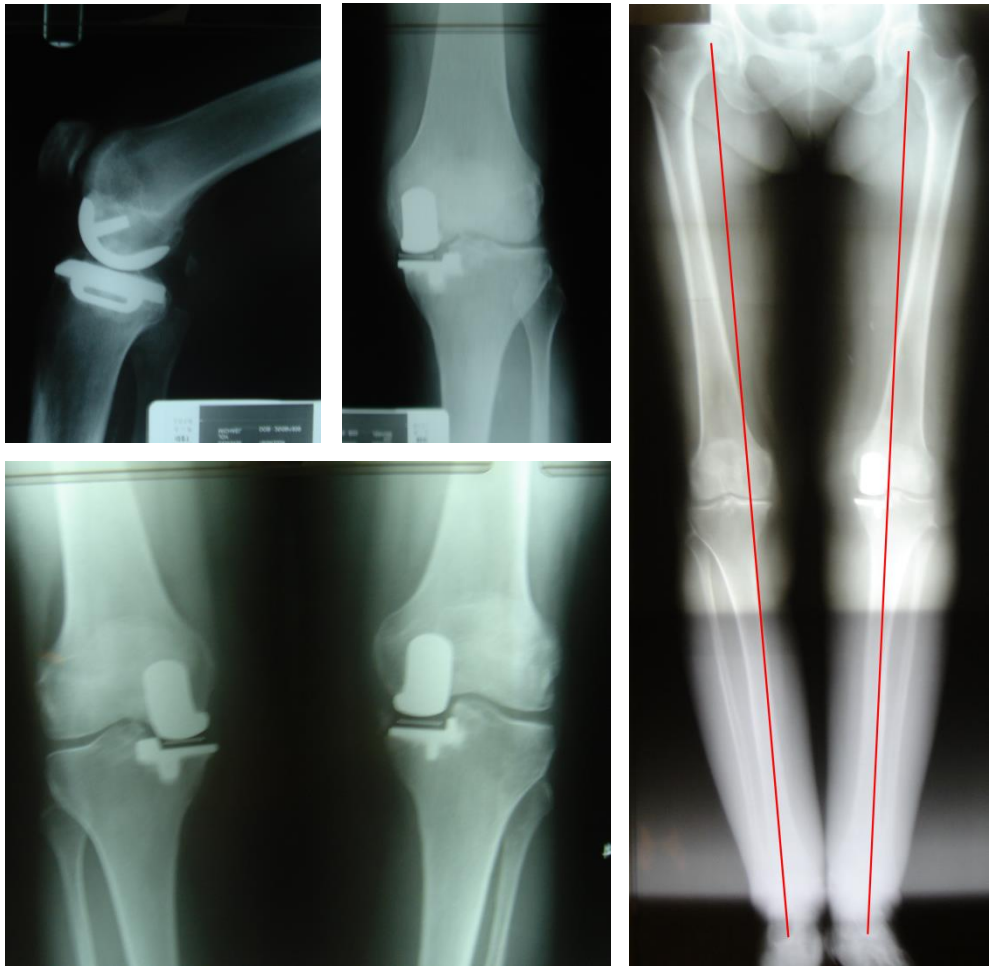
www.orthosupplier.com/players/images/mahe/product.jpg

www.orthomedex.com/medicalpowertools_pricelist.html

Conventional Surgery

Technology in Orthopaedics

POST OPERATIVELY



Conventional Surgery

Technology in Orthopaedics

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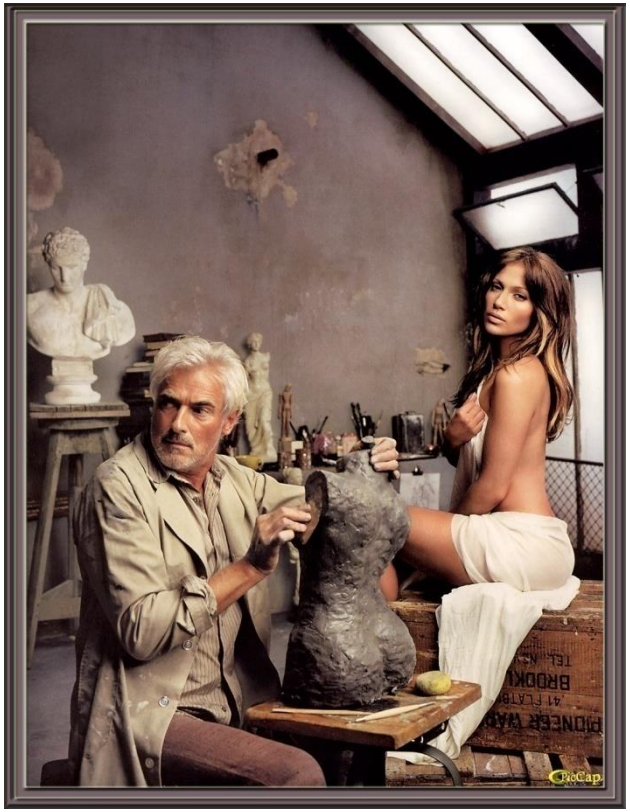
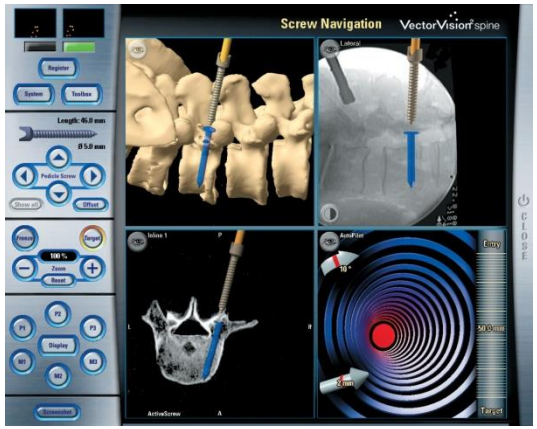


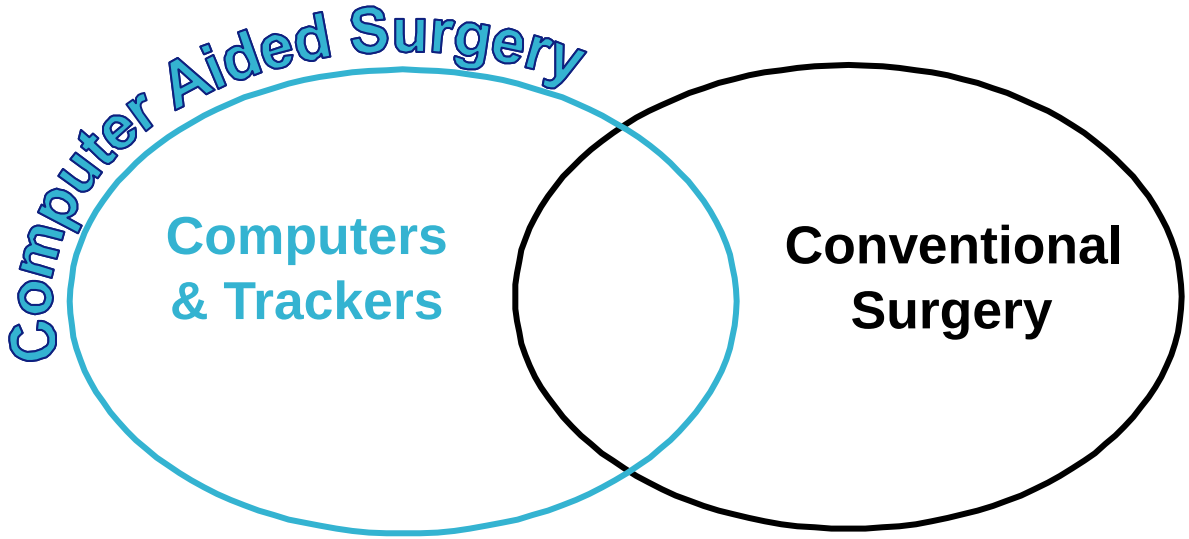
Conventional Surgery

Technology in Orthopaedics

www.ndigital.com



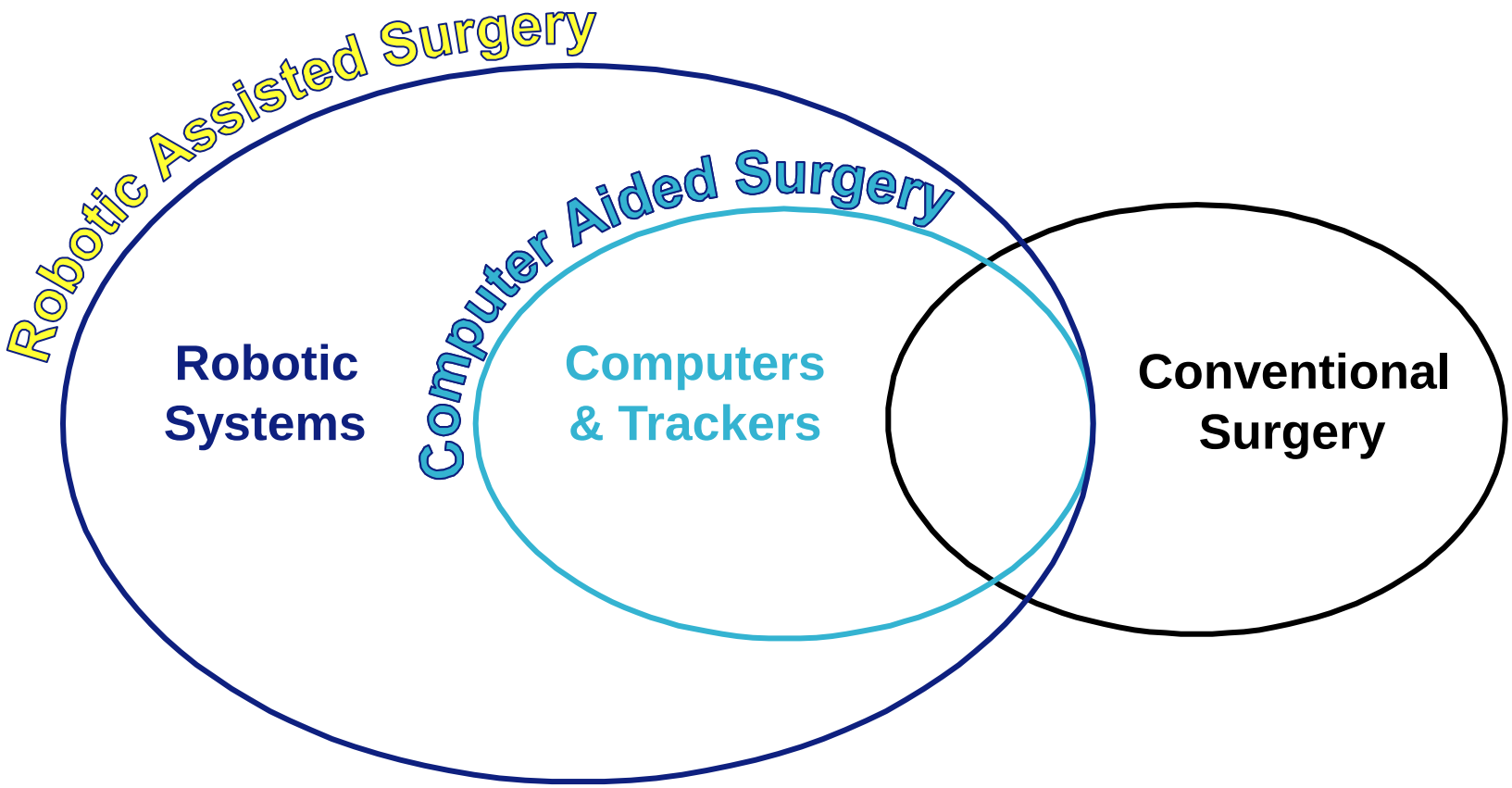
www.brainlab.com



Computer Aided Surgery

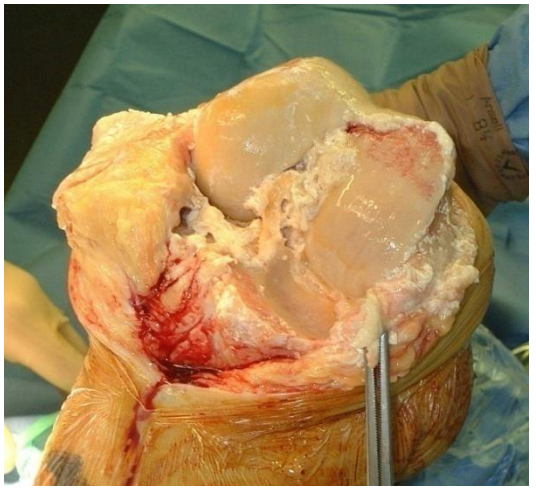
- CAS systems in orthopaedics
  - BrainLab GmbH Hip & Knee Navigation
  - B-Brown's Orthopilot™
  - Stryker Navigation™
  - Medtronic StealthStation S7™
  - BIOMET3i™ Navigator®
  - Zimmer's ORTHOsoft® family
  - Etc.

Technology in Orthopaedics



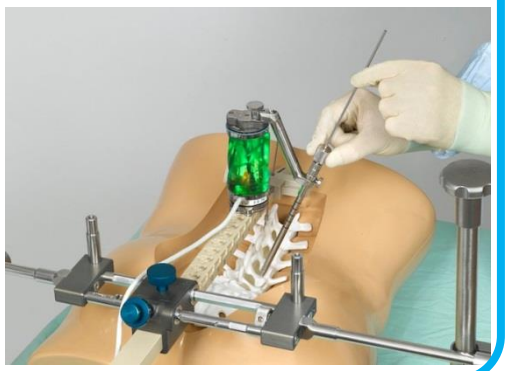
Robotic Assisted Surgery

- 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/)



NavioPFS®
(*www.bluebelttech.com*)

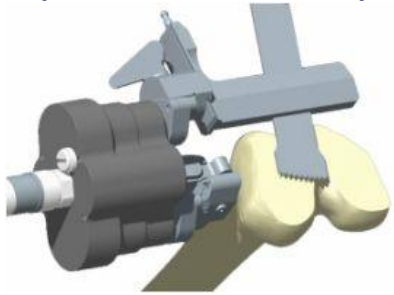
ACTIVE

ROBODOC
(*www.robodoc.com*)

COOPERATIVE

RIO®
(*www.makosurgical.com/*)

iBlock®
(*www.omnils.com*)



PASSIVE

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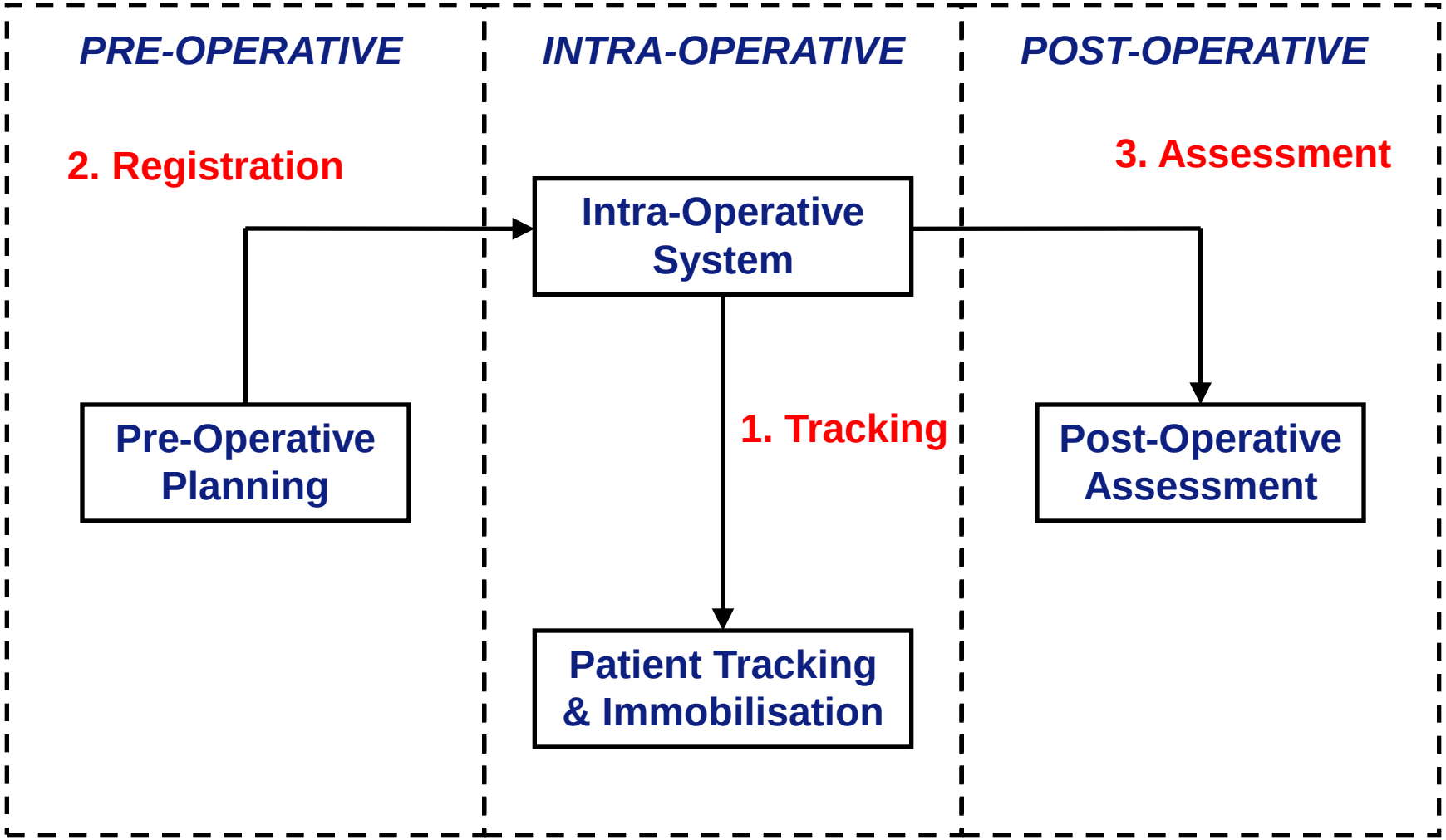
The Building Blocks of MRCAOS



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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

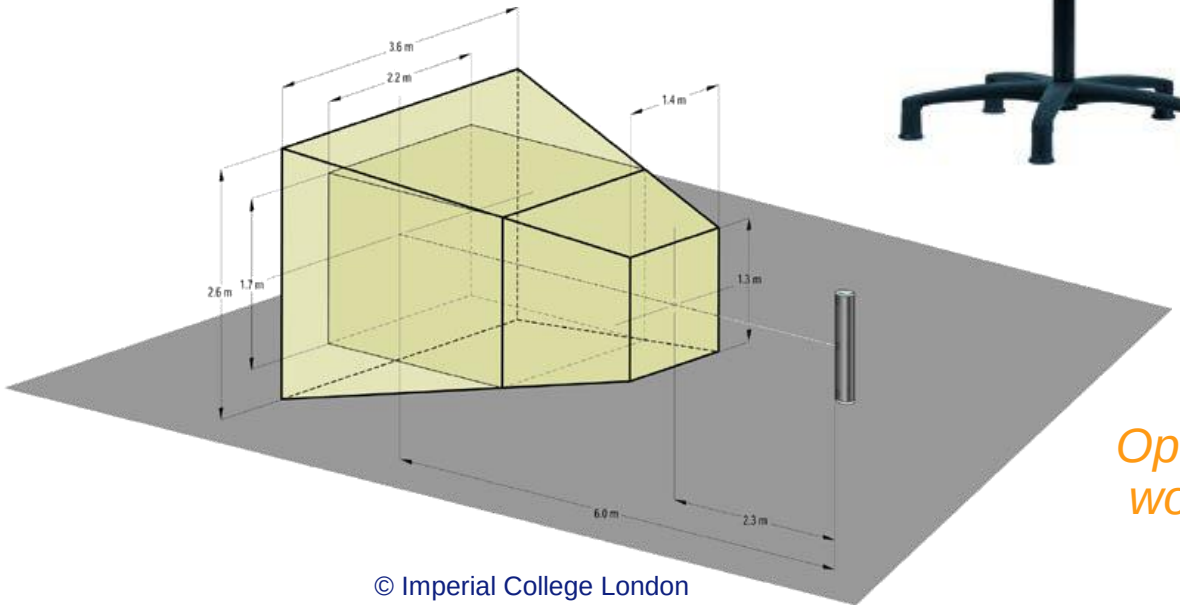
Transparent tracking!

IR-Based Trackers

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

Optotrack Certus® (www.ndi.com)

VectorVision® (www.brainlab.com)



Optotrack Certus® working envelope

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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

Sensor Stands

Passive IR Markers

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)

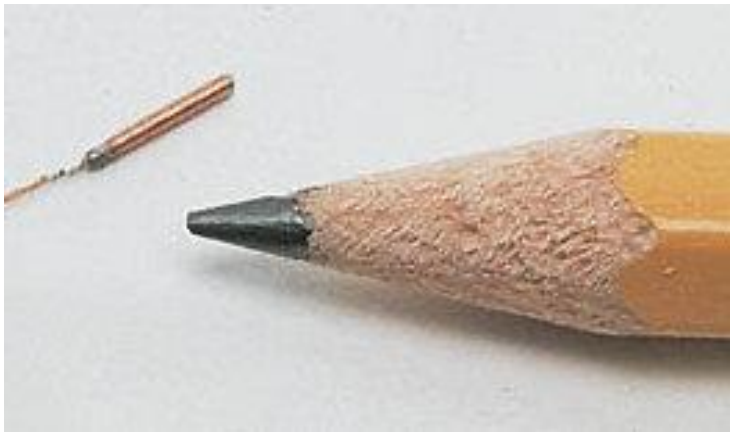
Electromagnetic Tracking

- Pros
  - ✓ Transparent function
  - ✓ Tiny sensors
  - ✓ Compact

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

Aurora®
(www.ndi.com)

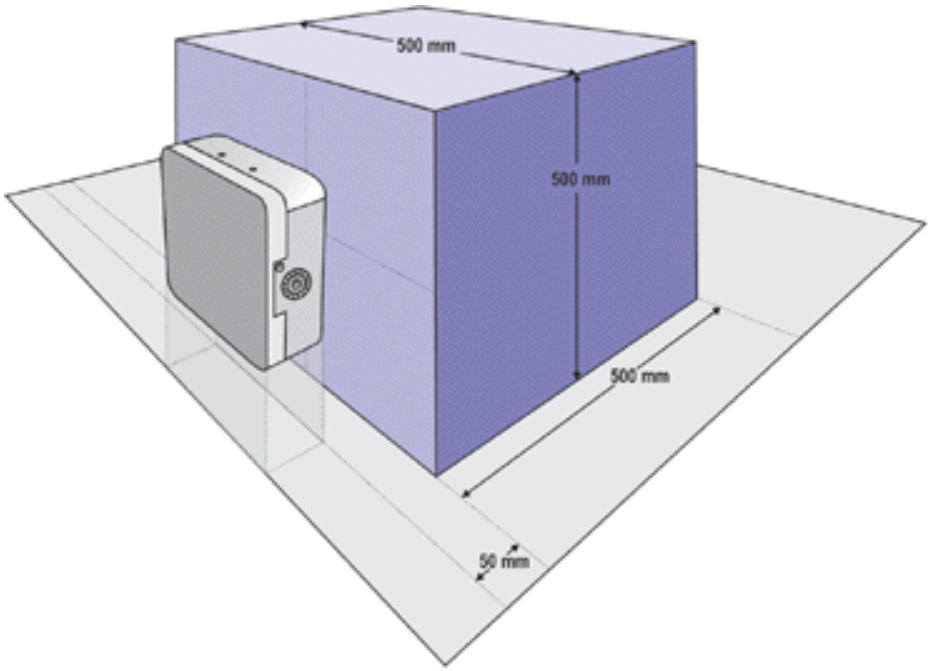
Aurora® embedded sensors



Electromagnetic Tracking

- Pros
  - ✓ Transparent function
  - ✓ Tiny sensors
  - ✓ Compact
- Cons
  - ✖ Small working envelope
  - ✖ EM Interference
  - ✖ Wired connections
  - ✖ High disposables cost

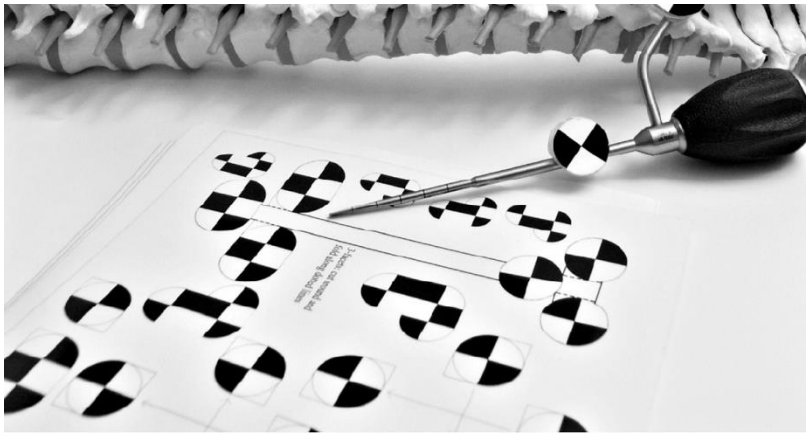
Aurora® working envelope



Digital Camera Tracking

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

MicronTracker2® DuraMarks

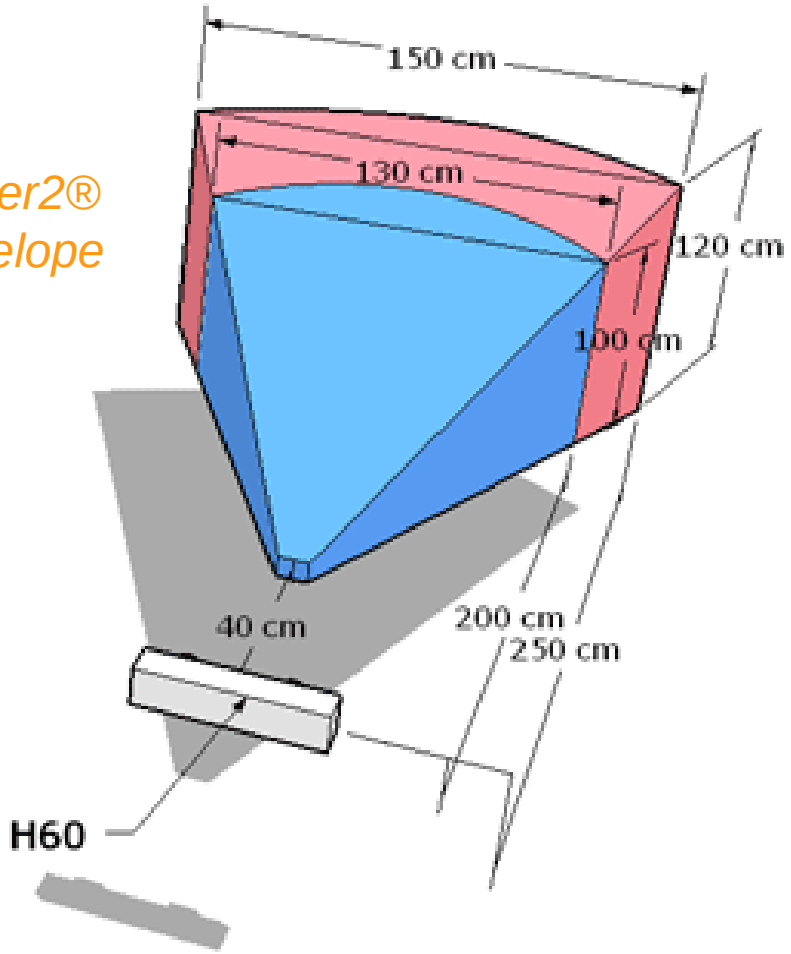


MicronTracker2®
(www.clarontech.com)

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

	IR	Mechanical	Magnetic	Optical
Minimally Invasive	χ	χ	√	χ
Line of sight	χ	√	√	χ
Robustness	χ	√	χ	χ
Working envelope	√	χ	χ	χ
Tracked objects	√	χ	χ	√
Compactness	χ	√	√	χ
EM Interference	√	χ	χ	√
Wired connections	√	√	χ	√
Poor depth resolution	χ	χ	χ	√
High disposables cost	χ	√	χ	√
Warm-up time	√	√	√	χ
	5 √	6 √	4 √	5 √

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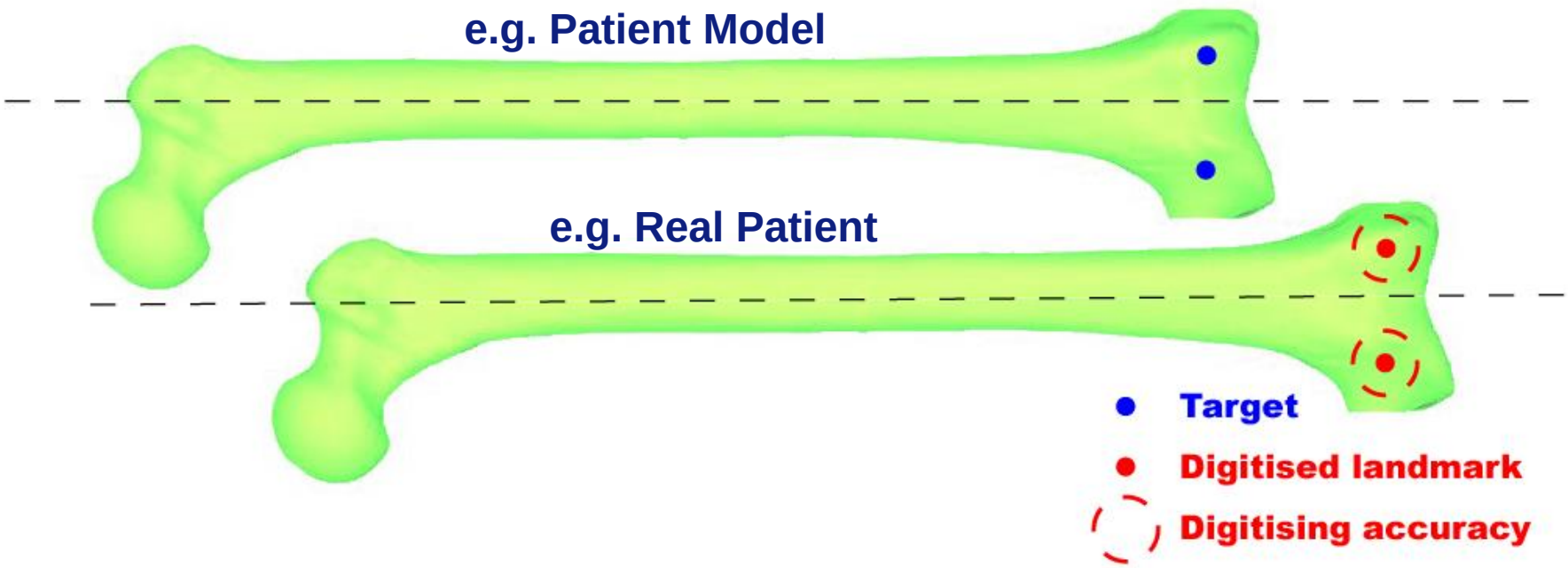
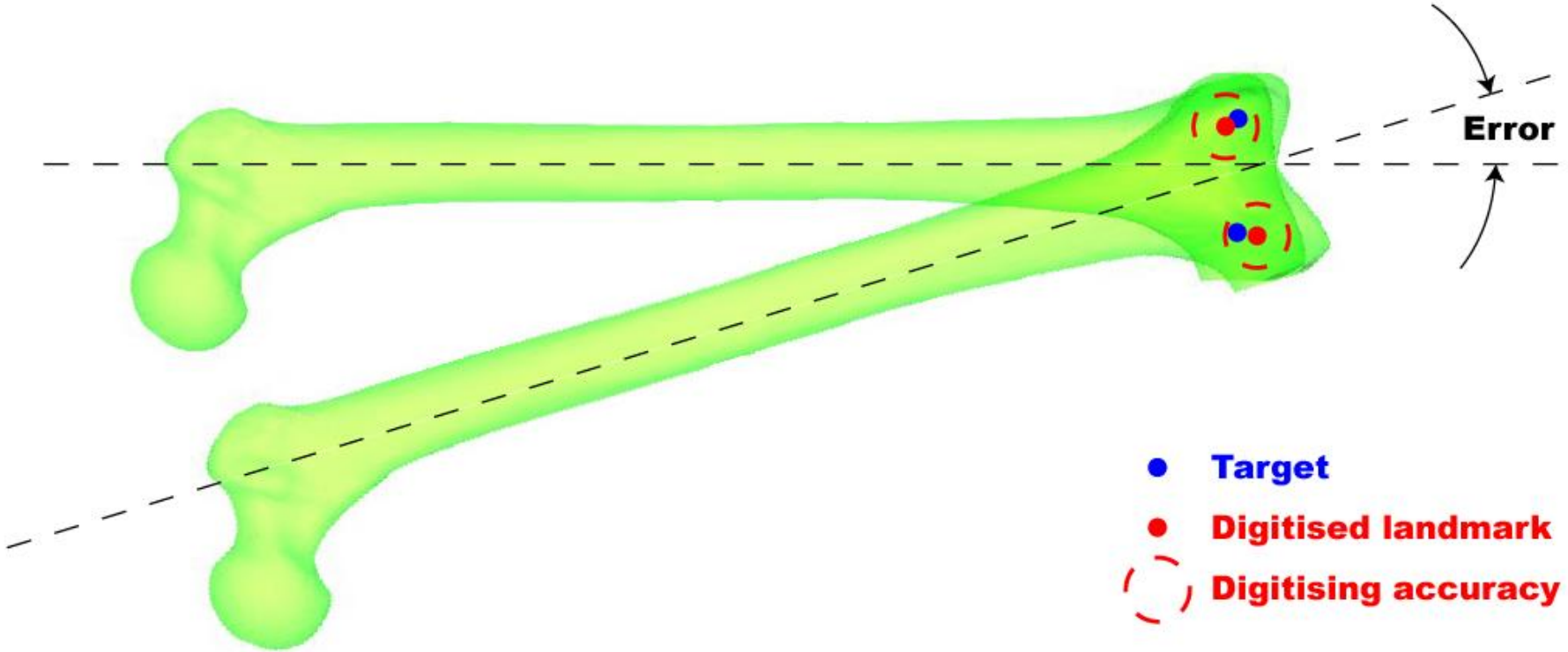
Intra-Operative Registration

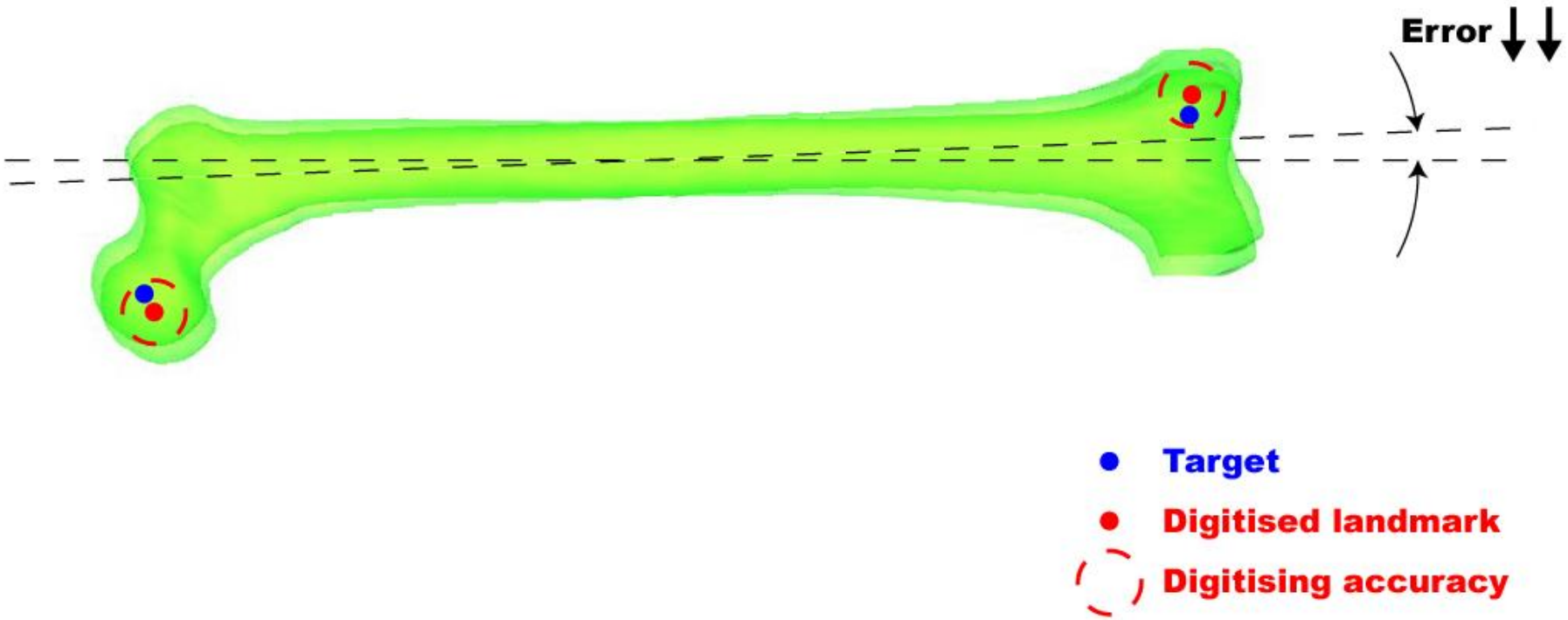
What is Registration



What is Registration



What is Registration



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

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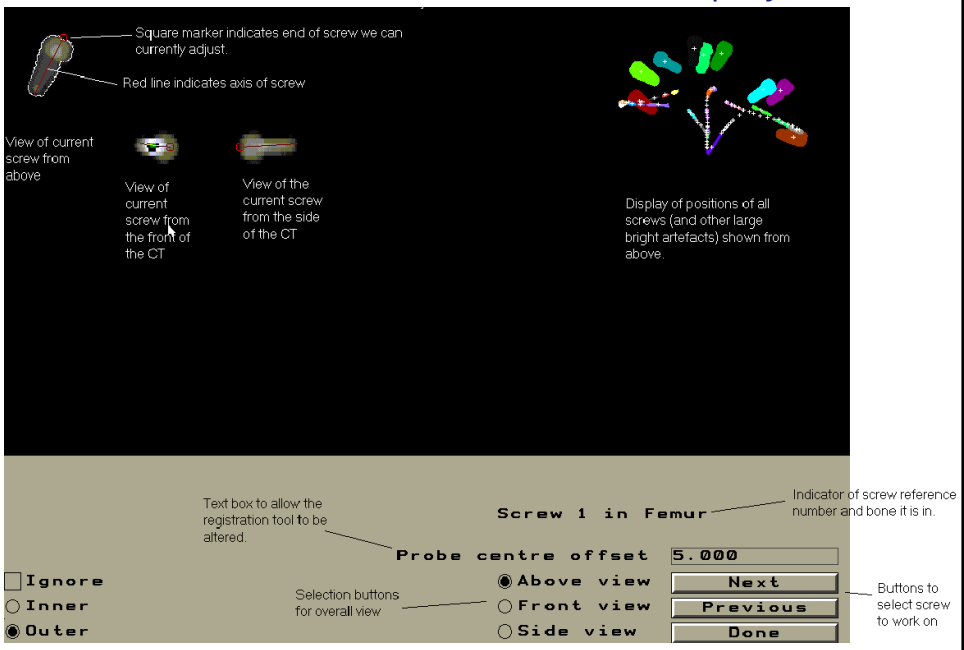
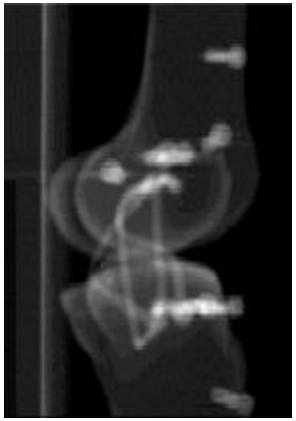
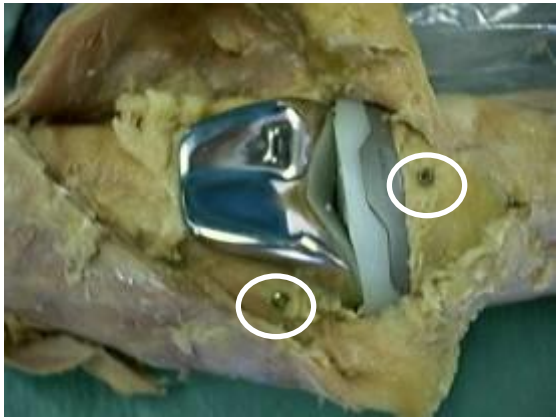






Registration Techniques

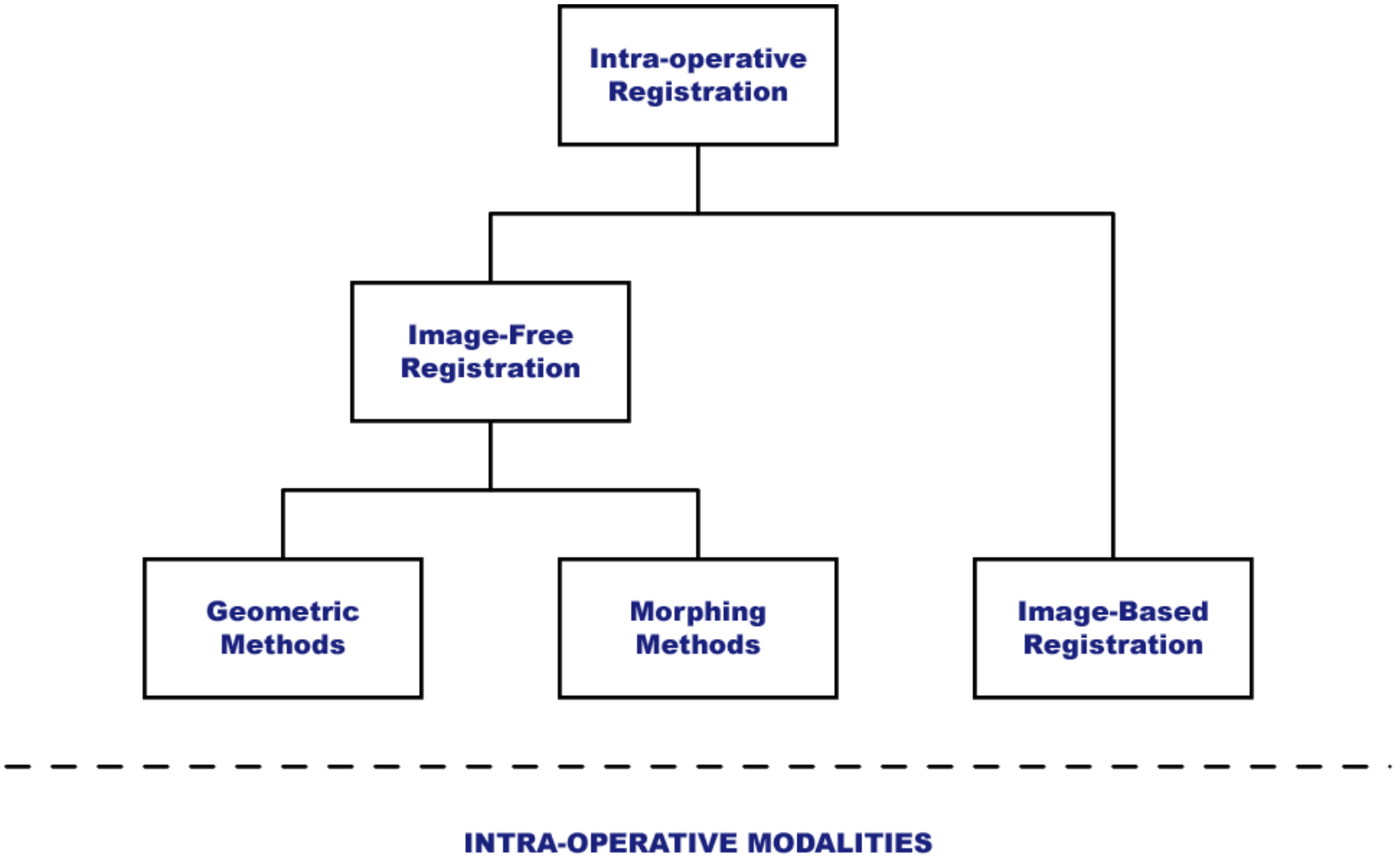
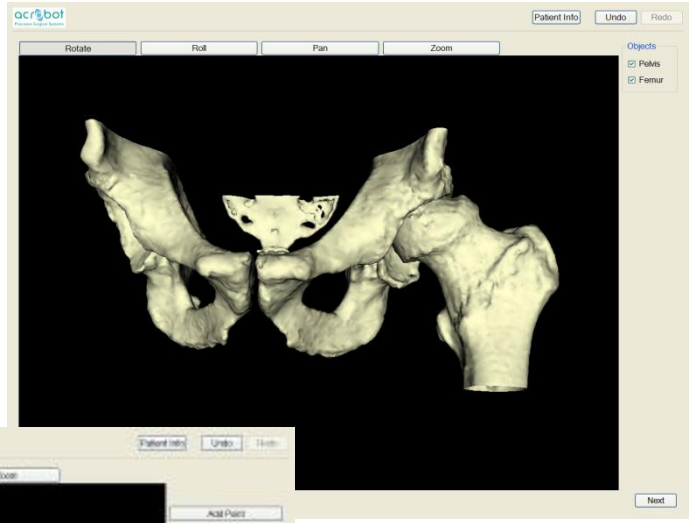
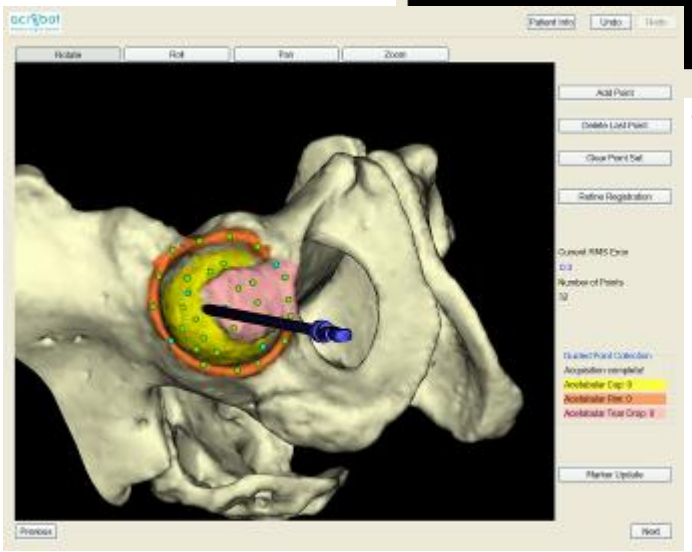


Image-Based - Mechanical Tracking





The Acrobot Company Ltd.

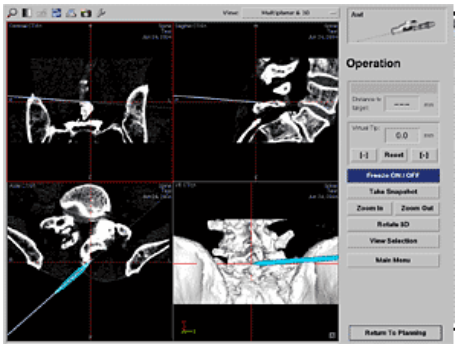
Image-Based - Optical Tracking

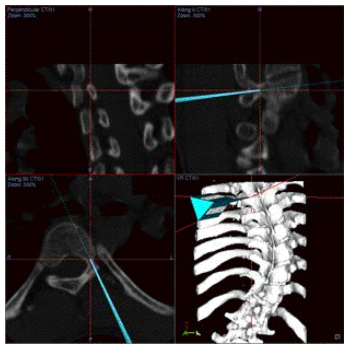
www.brainlab.com

Image-Based - Fluoroscopy

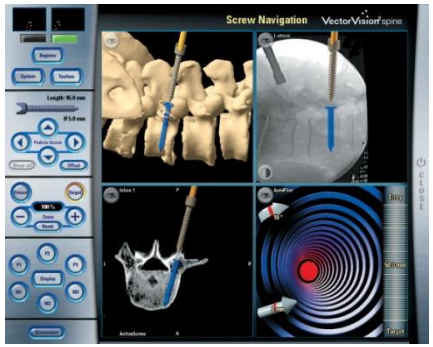
- Non-invasive modality
- Susceptible to intra-operative setup (e.g. instruments in field of view, patient orientation)
- Patient and surgeon radiation
- Cumbersome and obtrusive

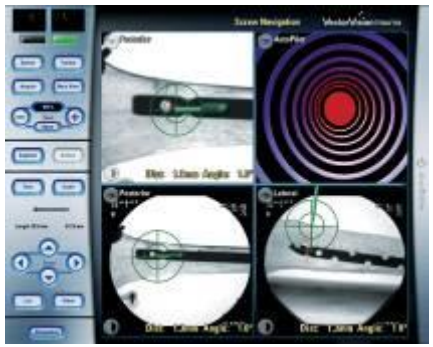
www.medical.siemens.com





www.stryker.com





www.brainlab.com

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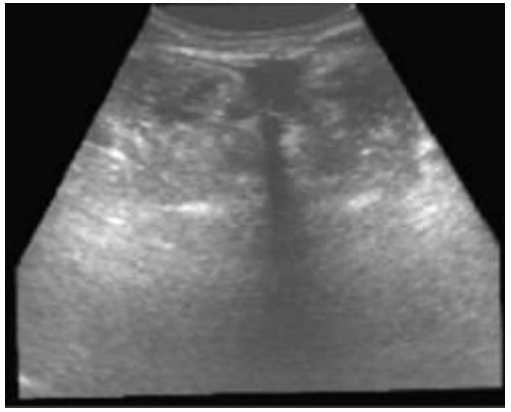
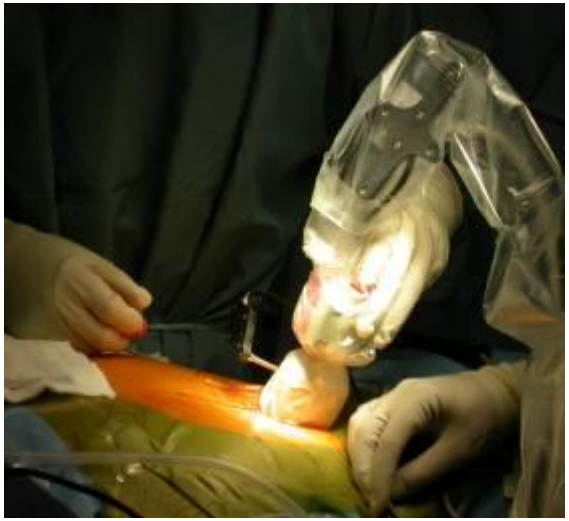
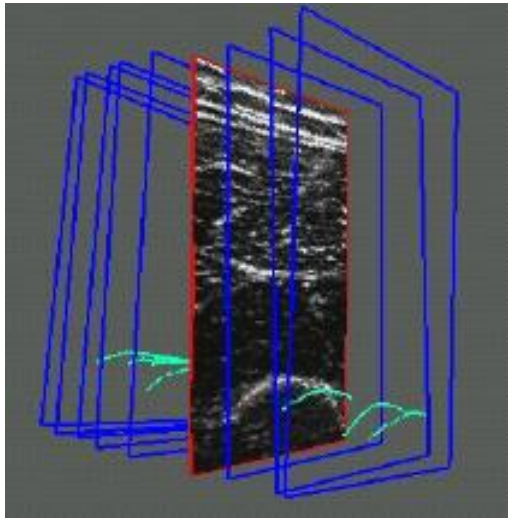
Image-Based - Ultrasound

- Non-invasive landmark aquisition
- 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

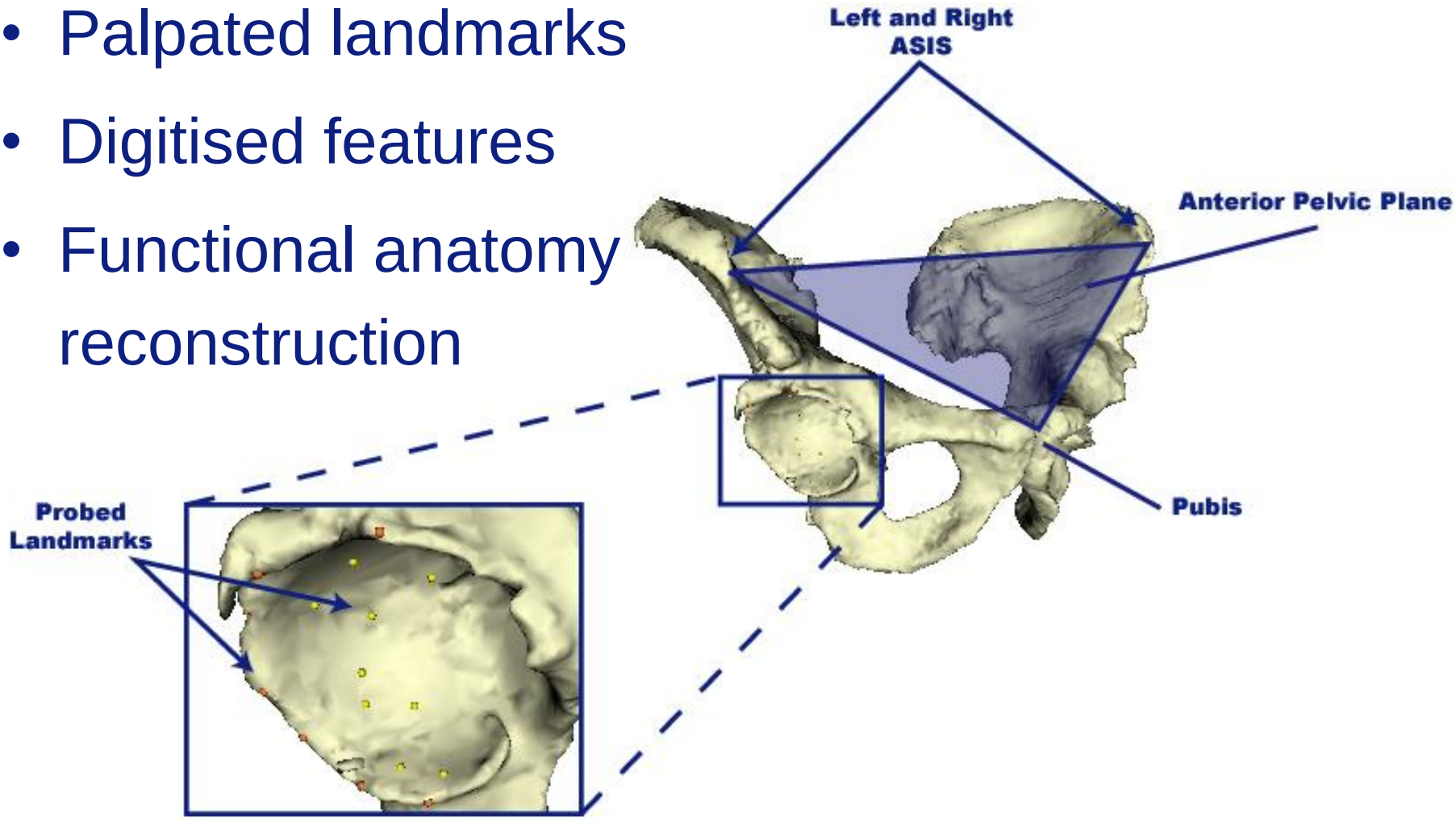
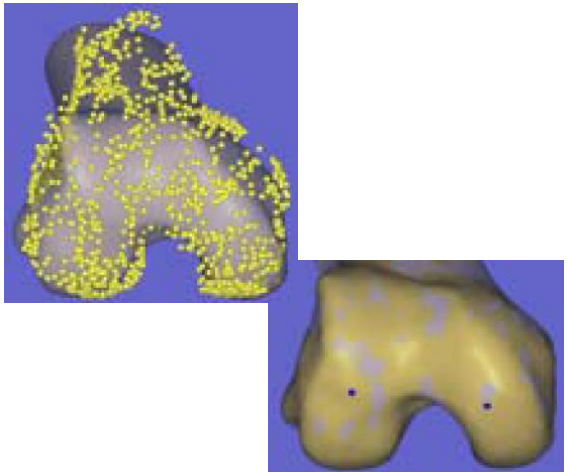


Image-Free - Morphing Methods

- 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**



www.praxim.fr

www.brainlab.com

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?

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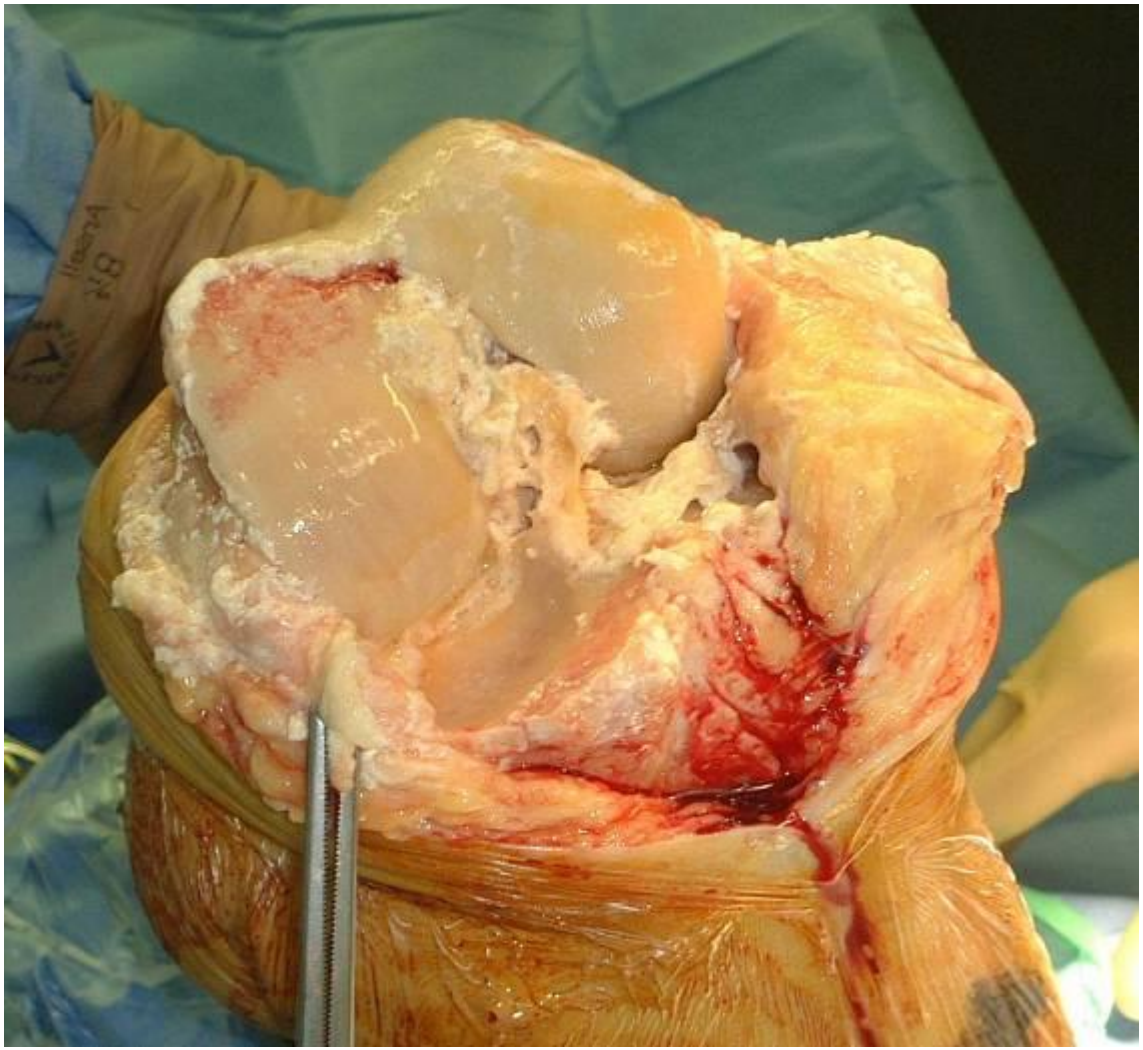
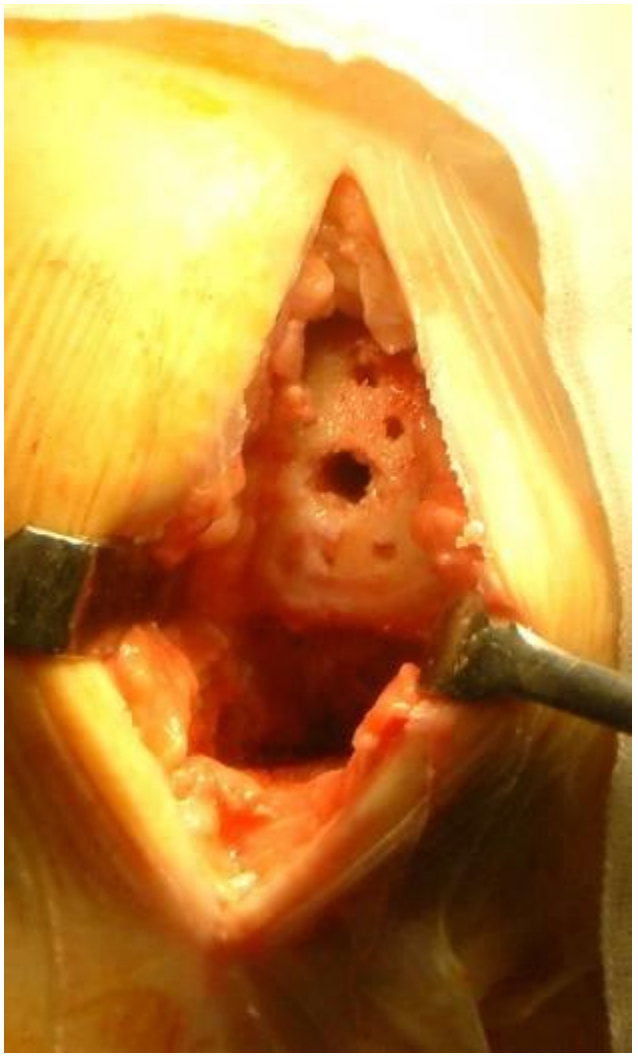
A Case Study: The Acrobot Success Story (sort of)

Imperial's Own Experience

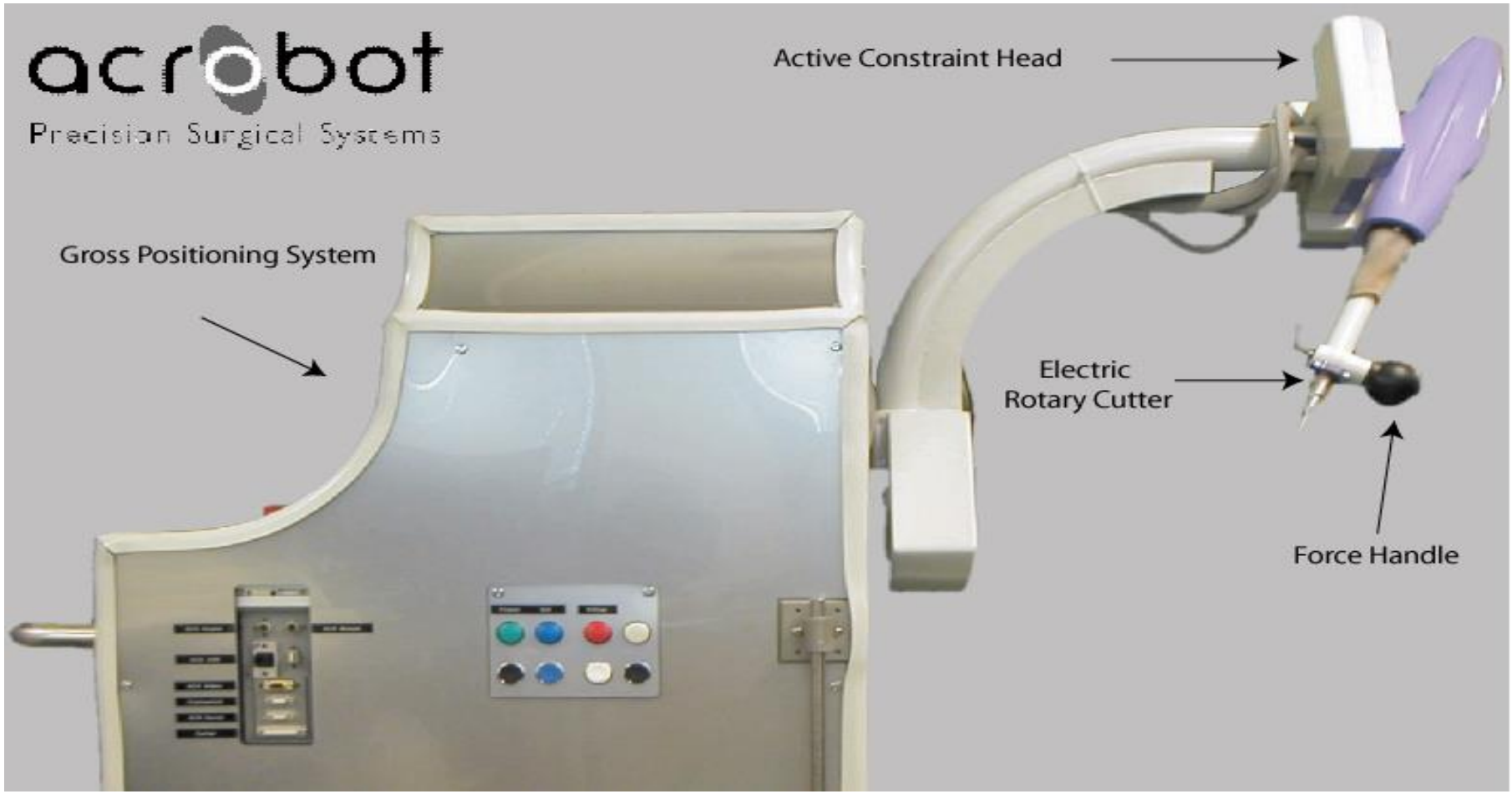
- "**Active-constraints**" robotics
  - **Force-controlled joystick** on end of robot
  - Surgeon moves, while **robot constrains** within a **pre-op plan**
  - Surgeon judges, senses, adapts - a good synergy
- **ACROBOT**
  - An **AC**tive constraint **ROBOT** for minimally invasive Unicomaprtmental Knee Arthoplasty (UKA)
  - **CT-based** plan (so image-based) & **mechanical tracking**

TKR or UKR?



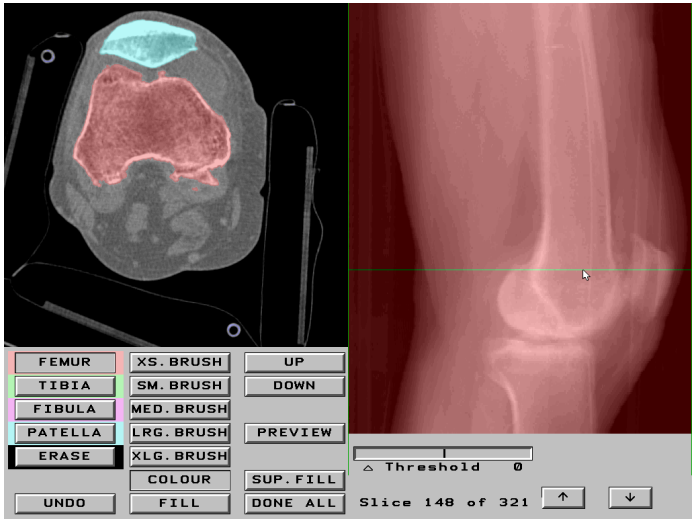


The ACROBOT System

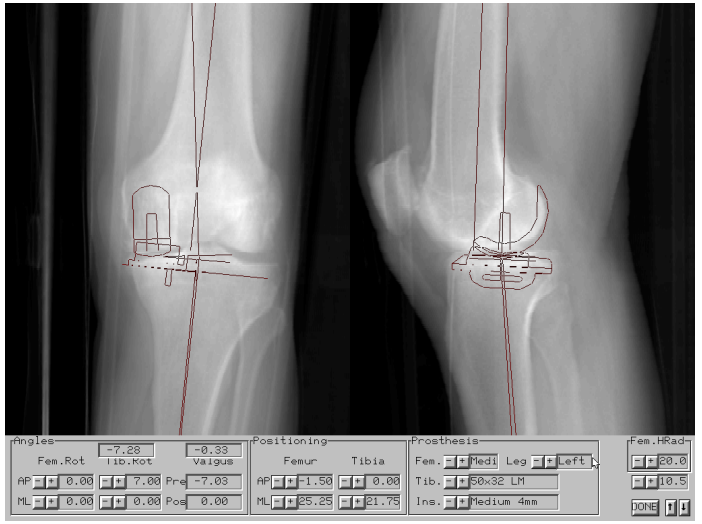


Preoperative Planning

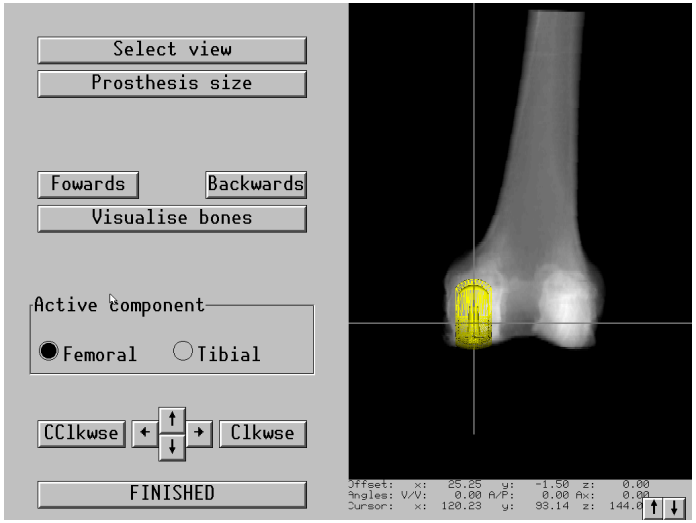
Segmentation



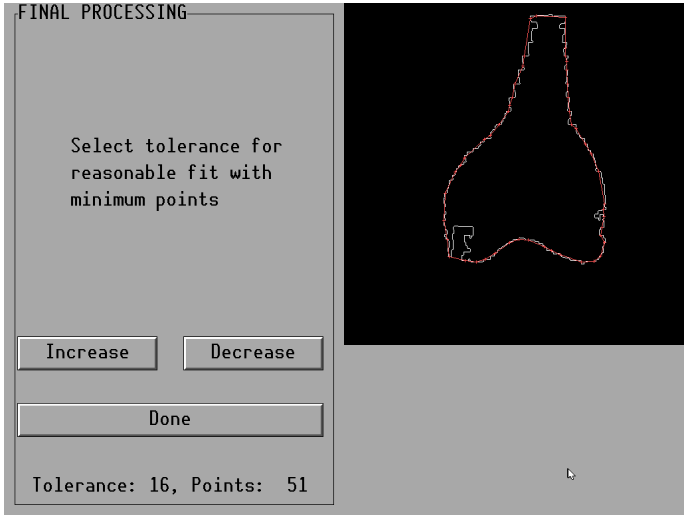
Mechanical Axis Alignment



Prostheses Alignment

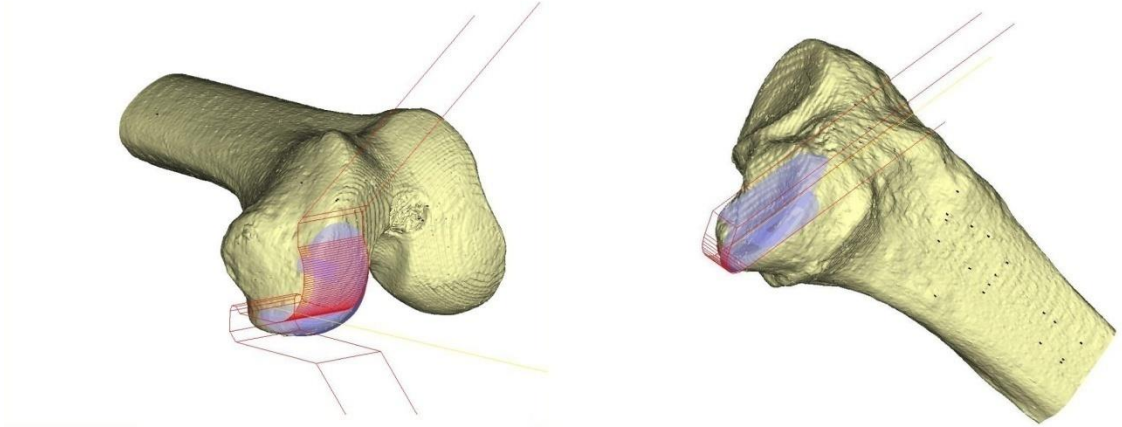


Boundary Generation

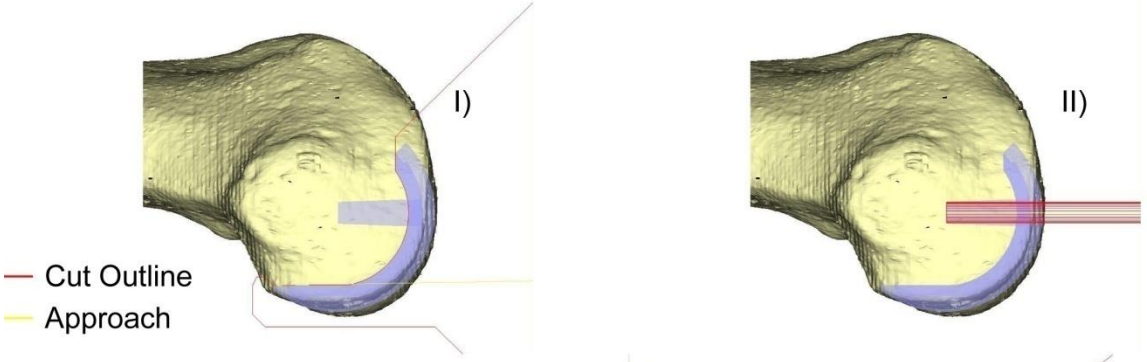


Constraints

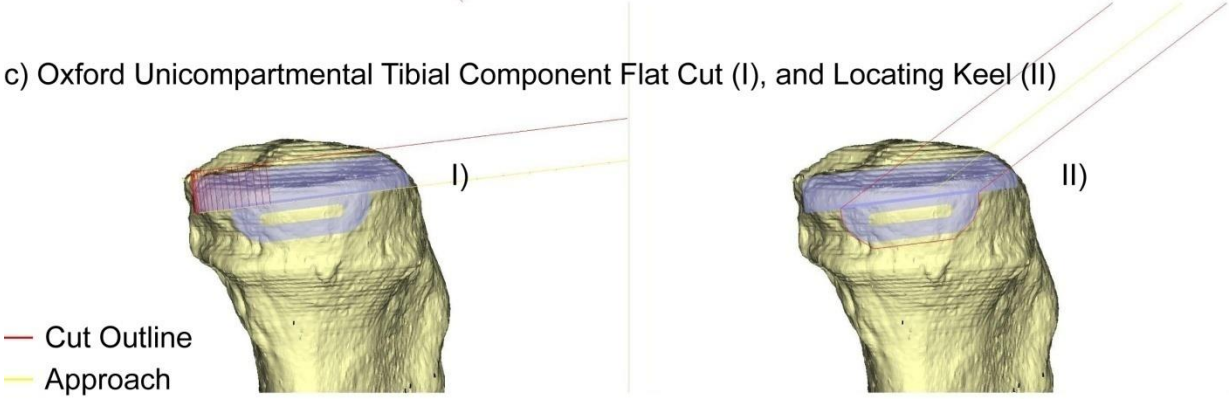
a) Oxford Unicompartmental Knee Implants on CT Generated Surface Models



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

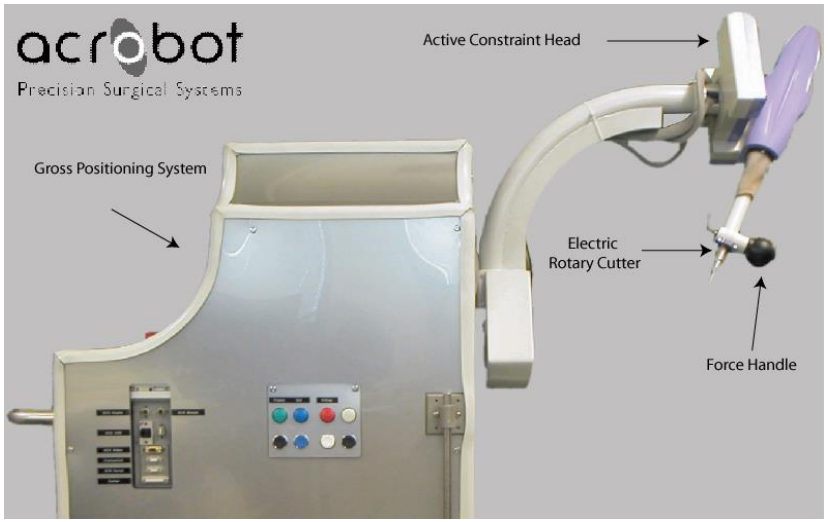


c) Oxford Unicompartmental Tibial Component Flat Cut (I), and Locating Keel (II)



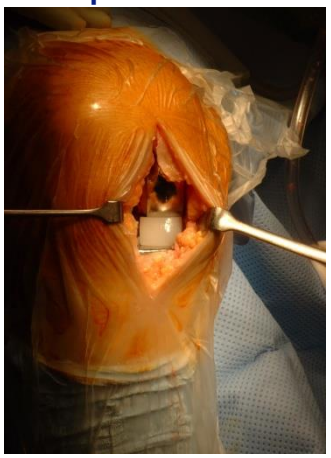
Intra-Operative Procedure

Intra-Operative system

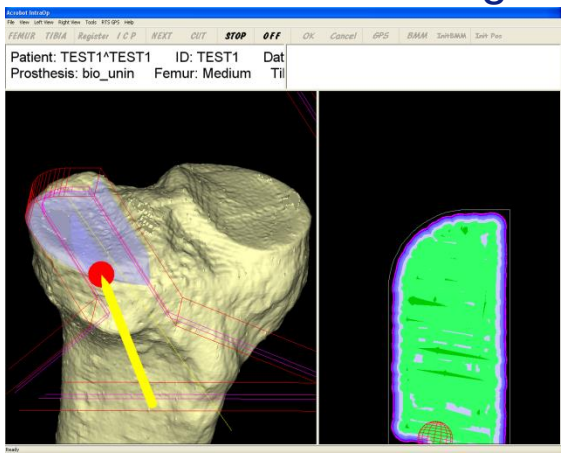


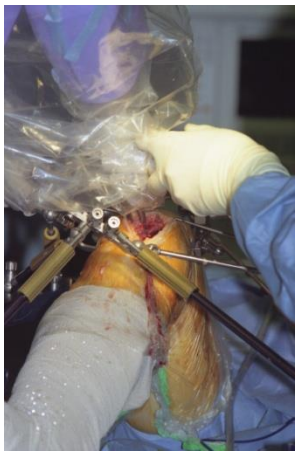
Registration

Implantation



Cutting





Robotic Assisted UKA

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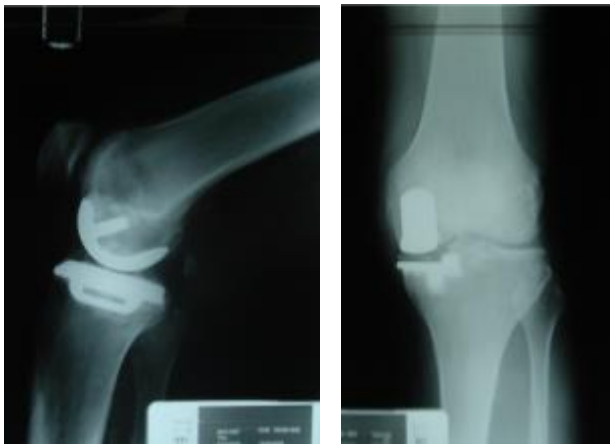
Post-Operative Assessment

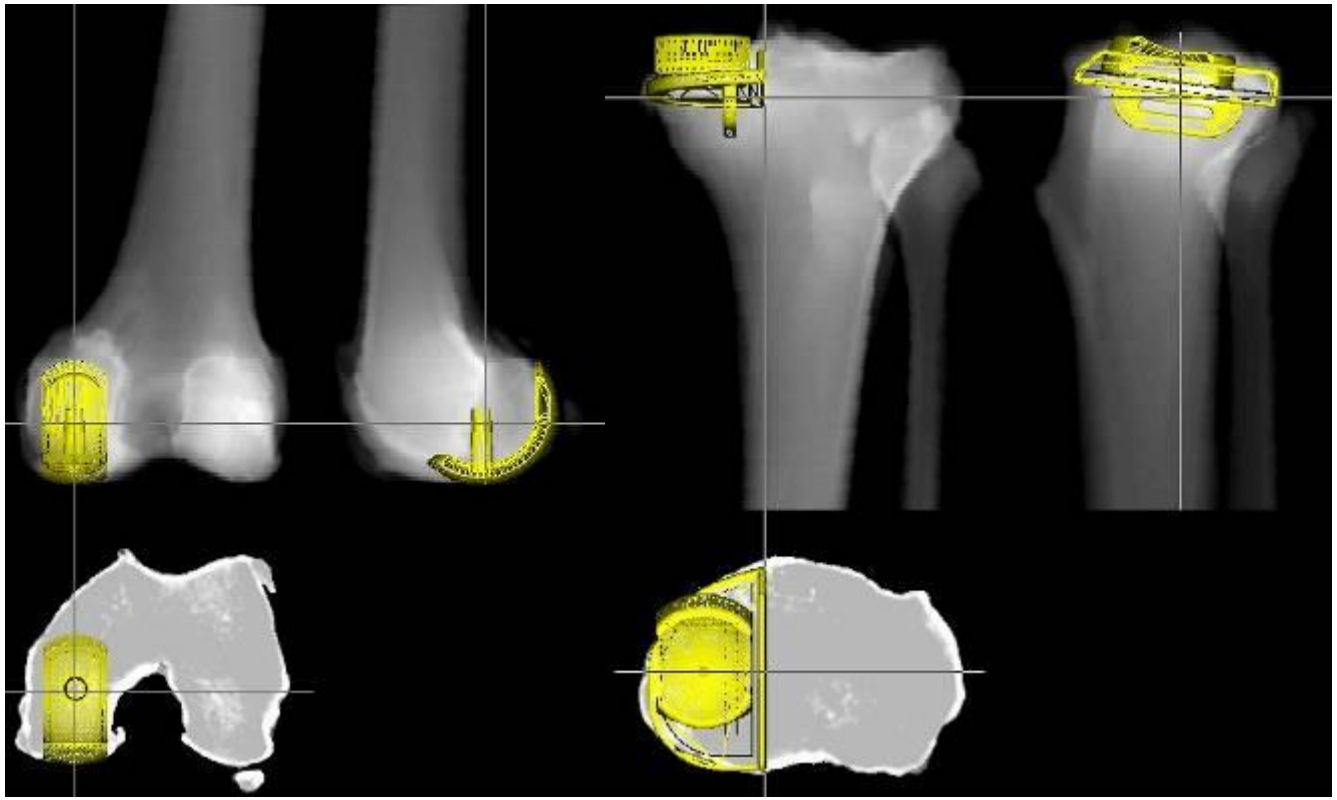
Current Practice

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



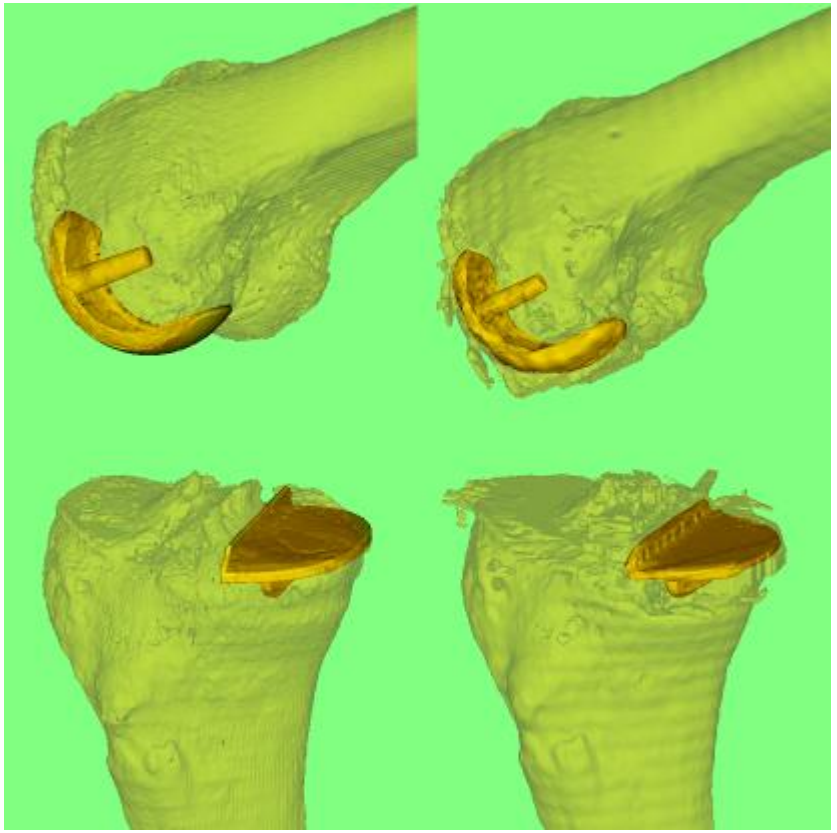
CT Based Assessment

1. Pre-Operative CT



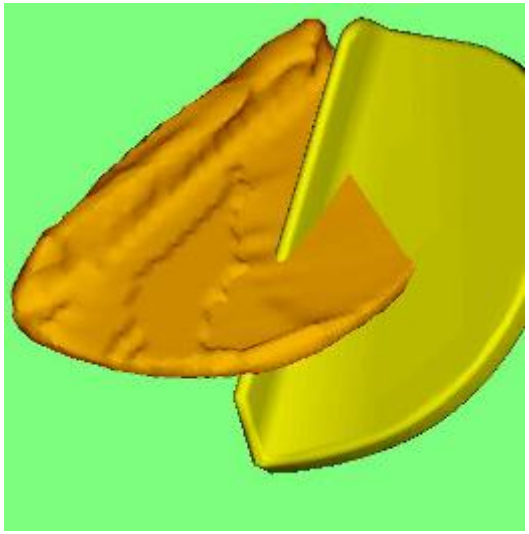
CT Based Assessment

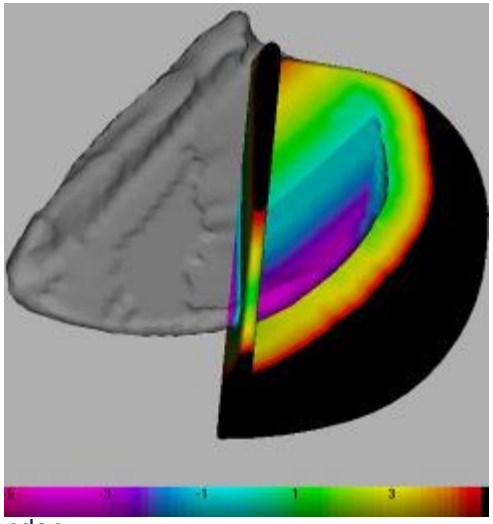
1. Pre-Operative CT
2. Post-Operative CT
3. assessment



CT Based Assessment

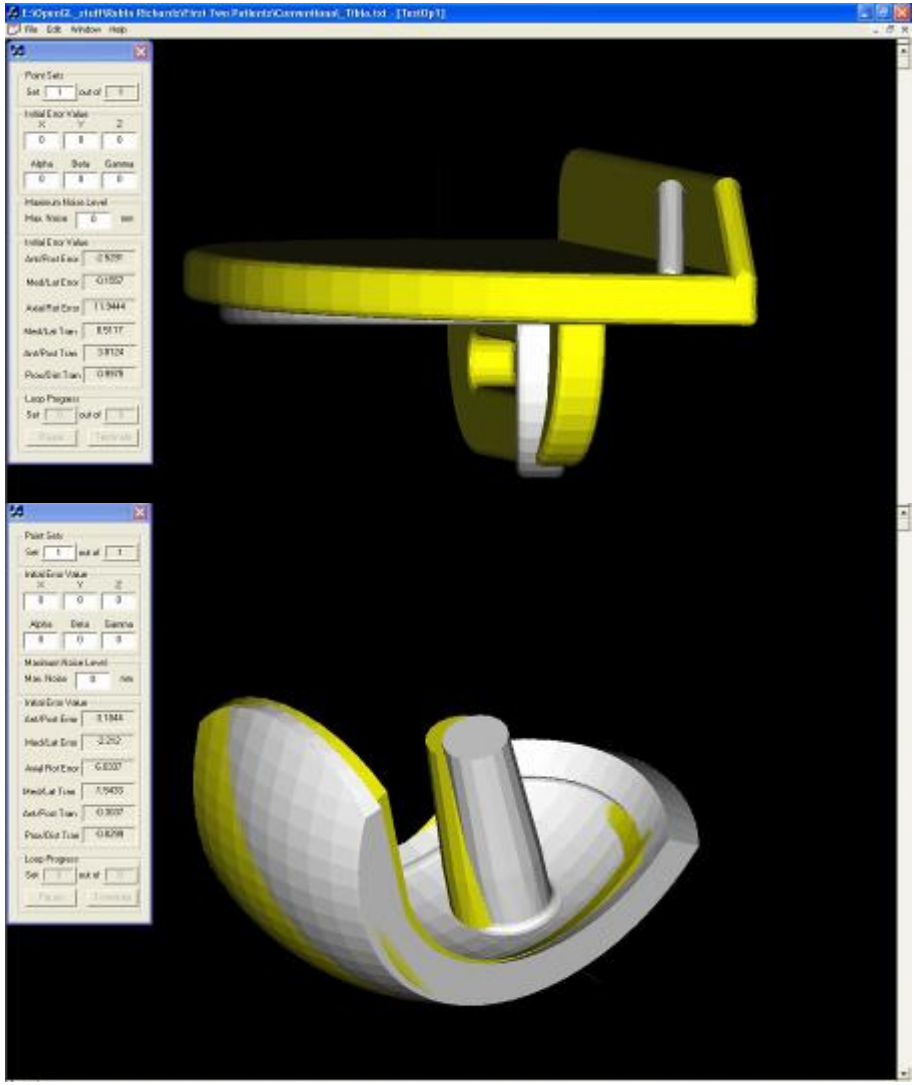
1. Pre-Operative CT
2. Post-Operative CT
3. Surface to surface registration





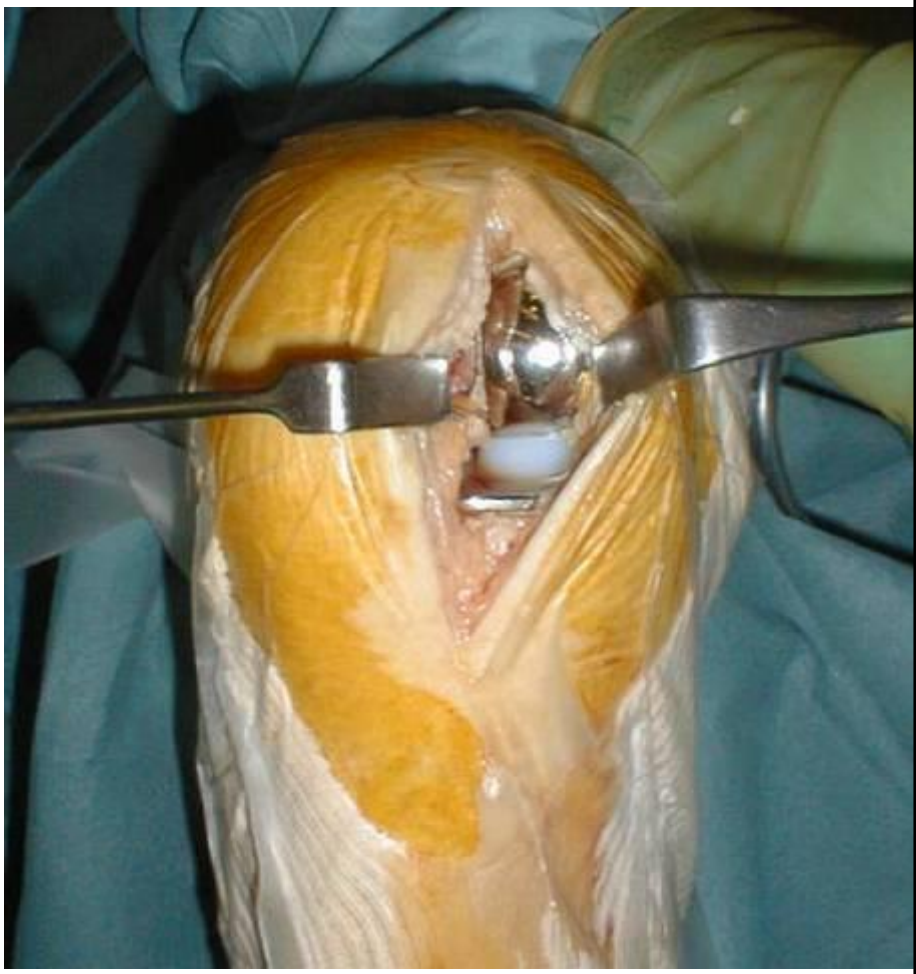
CT Based Assessment

1. Pre-Operative CT
2. Post-Operative CT
3. Surface to surface registration
4. Post-operative alignment error assessment

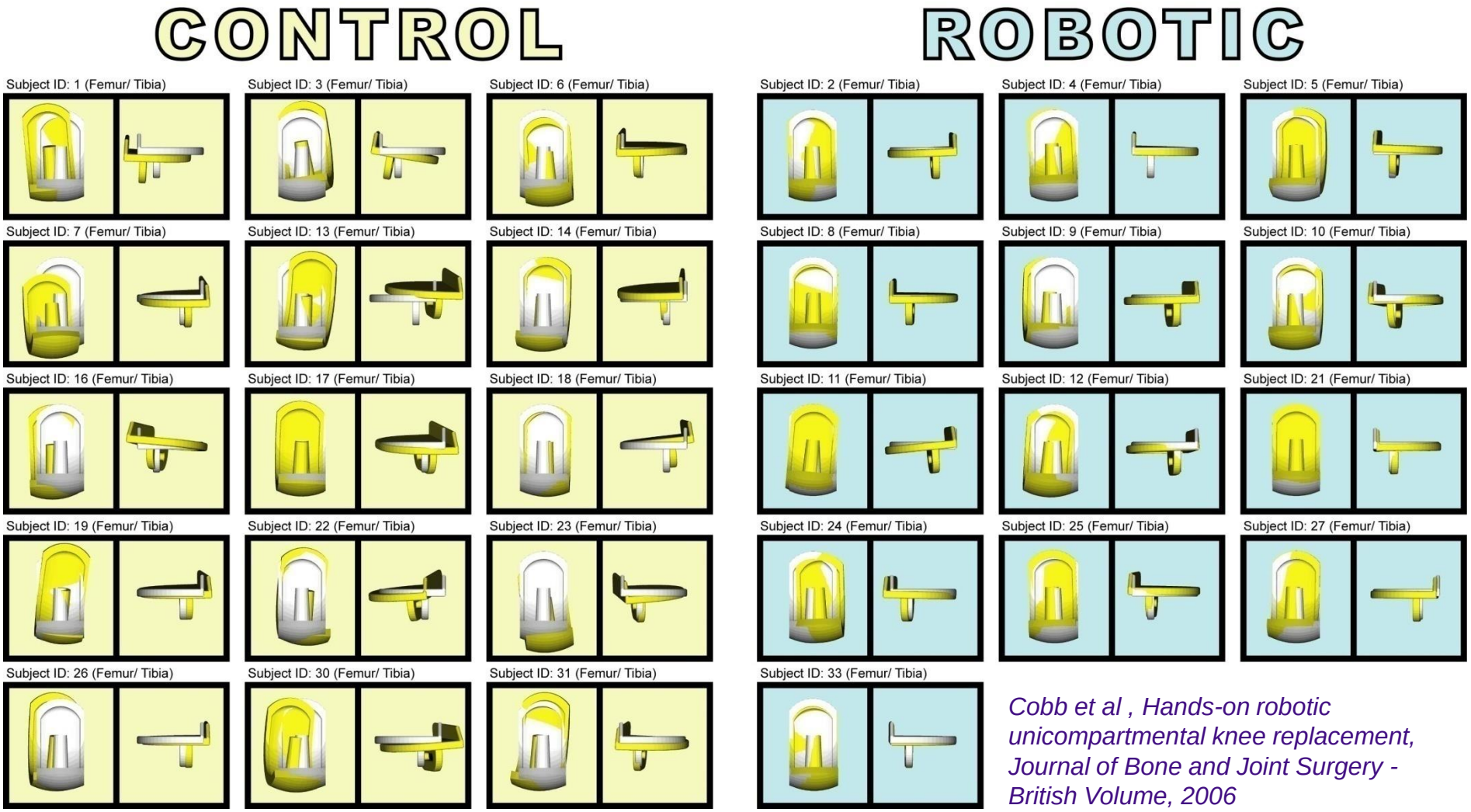


Robotic Uni-Condylar knee Trial

- 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



Cobb et al , Hands-on robotic unicompartmental knee replacement, Journal of Bone and Joint Surgery - British Volume, 2006

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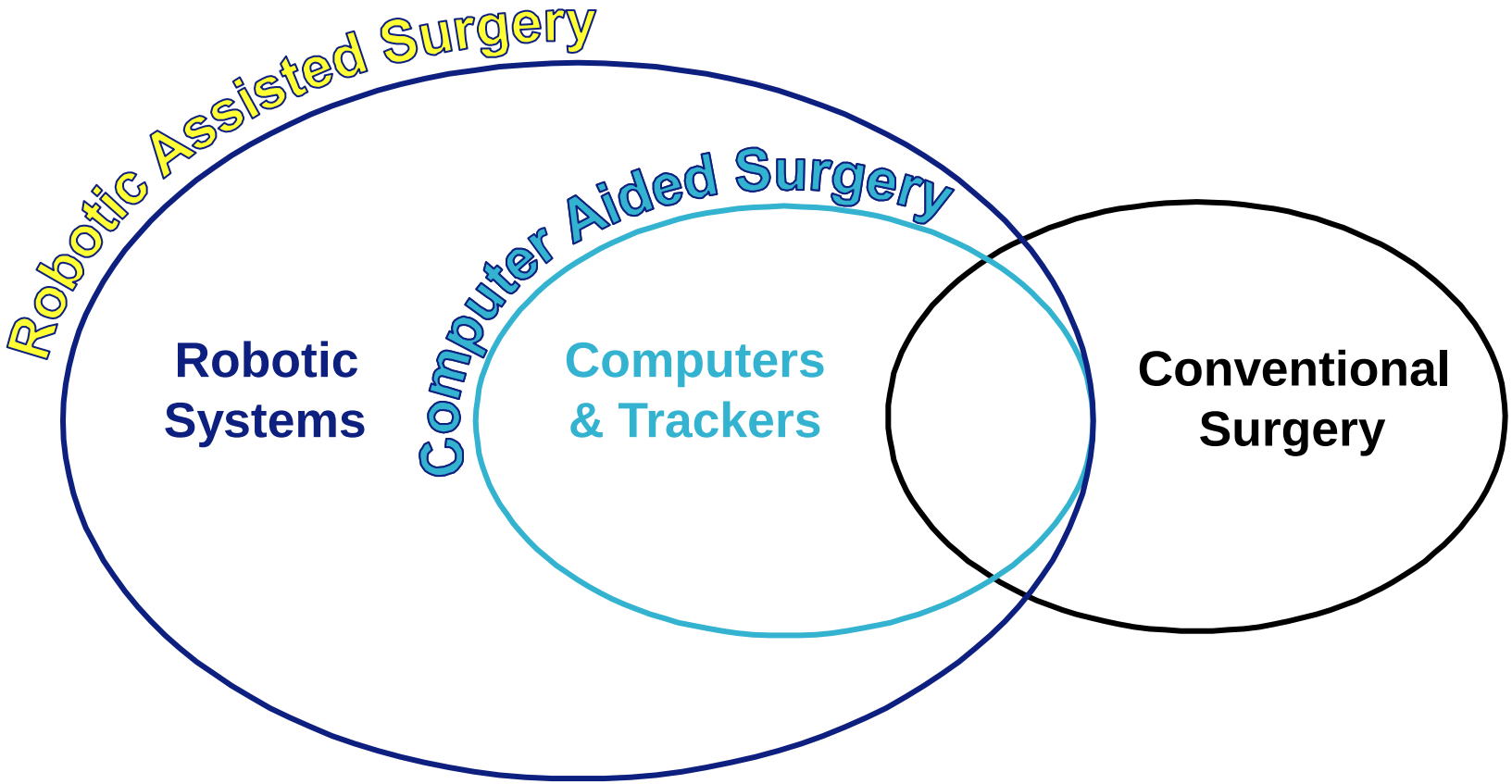
The Hurdles of Commercialisation

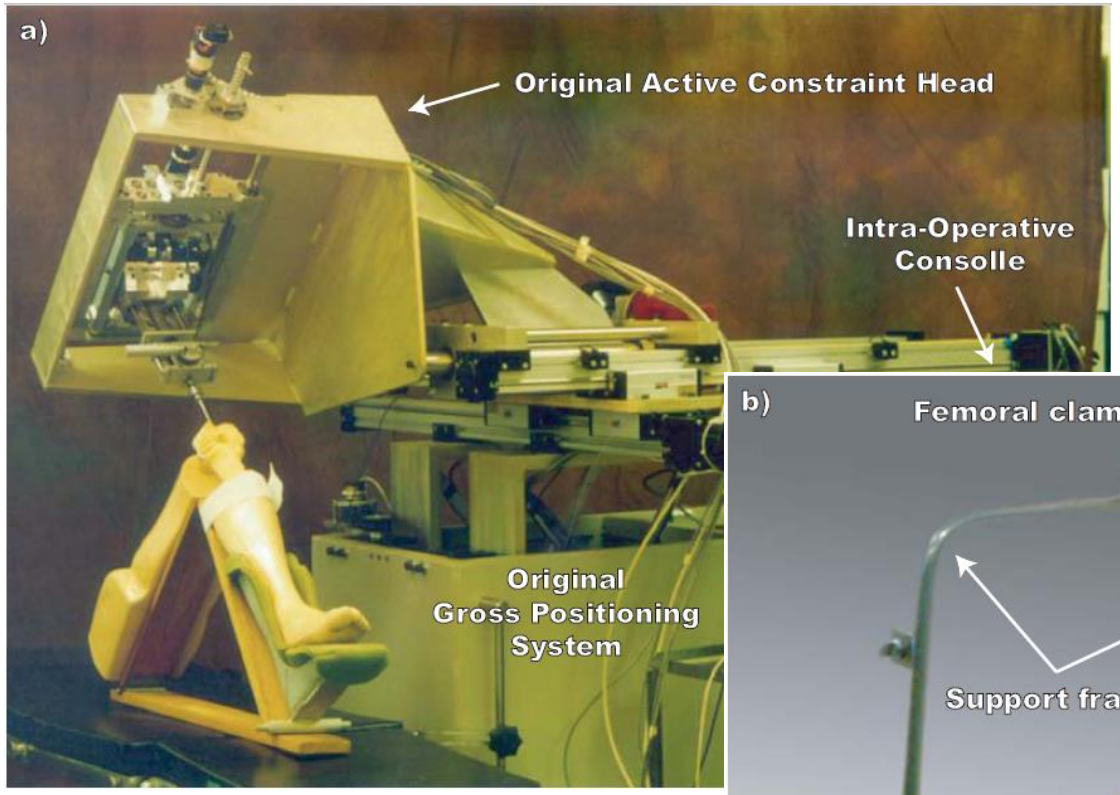
Technology in Orthopaedics



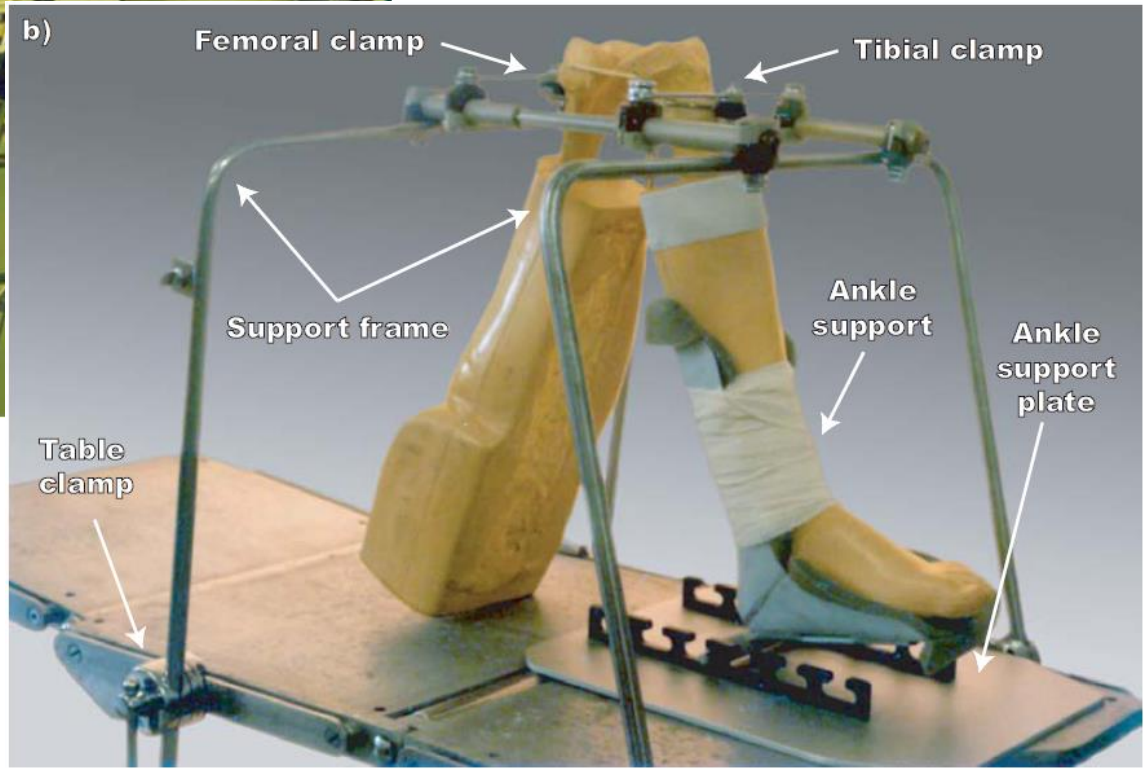
HIGHER COST/COMPLEXITY

BETTER SURGICAL ACCURACY (OUTCOMES?)

Now and Then…



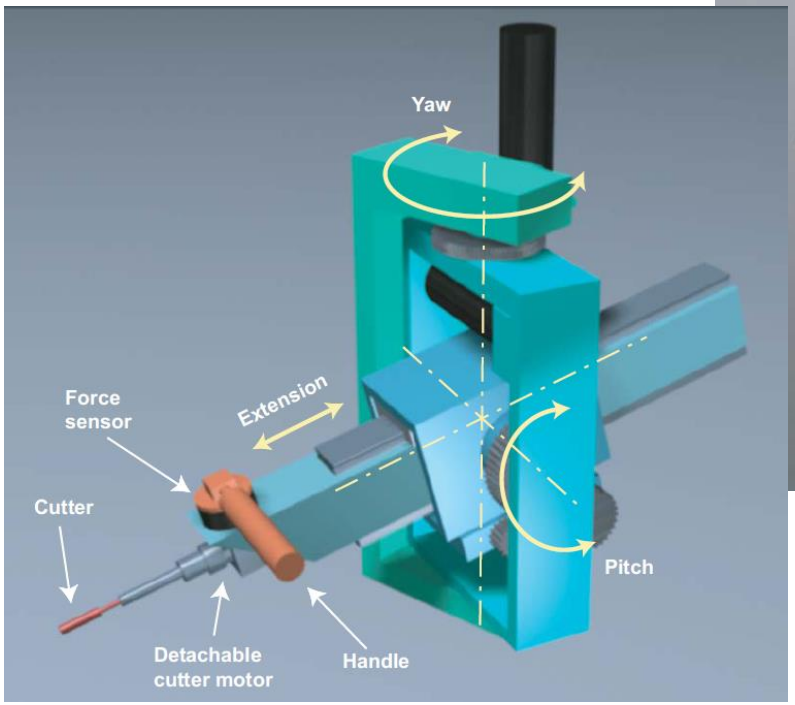
- Pre-2000 version
- First full prototype
- Cadaver trials

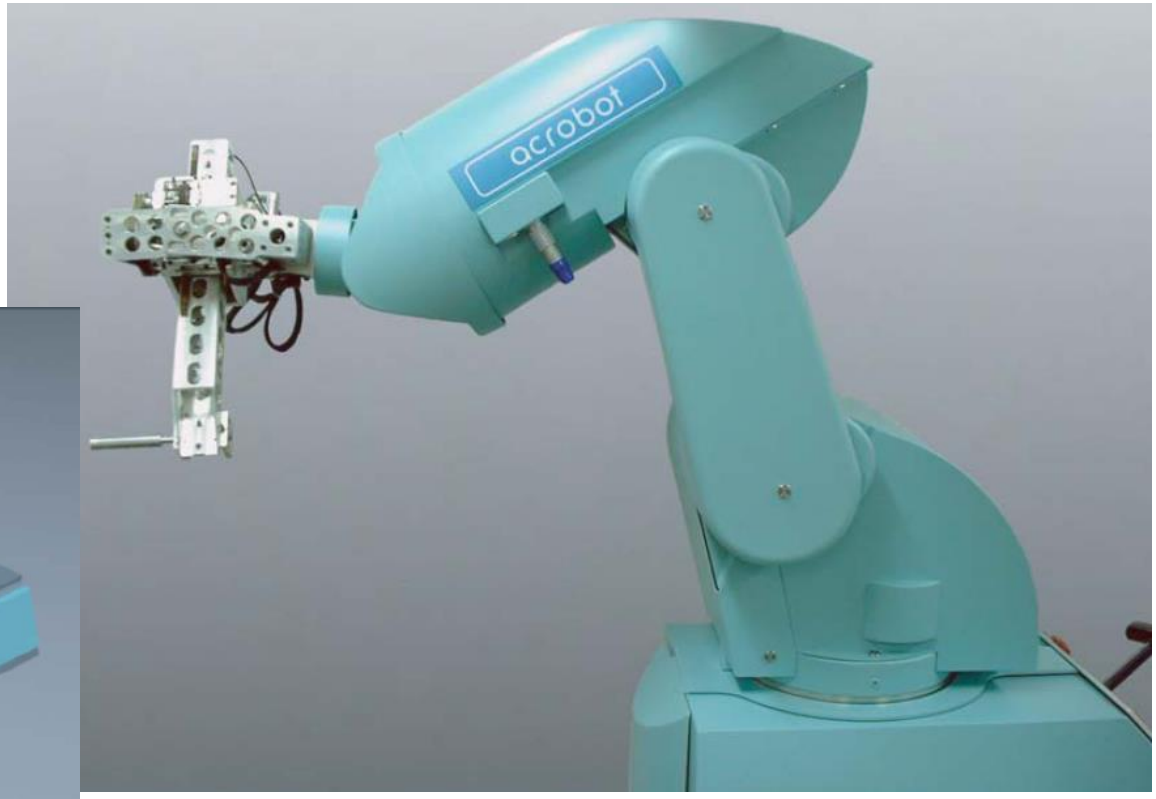


ACADEMIC RESEARCH
GREAT OPTIMISM

Now and Then…

- 2000-2003 version
- New gross positioner
- First TKA trials

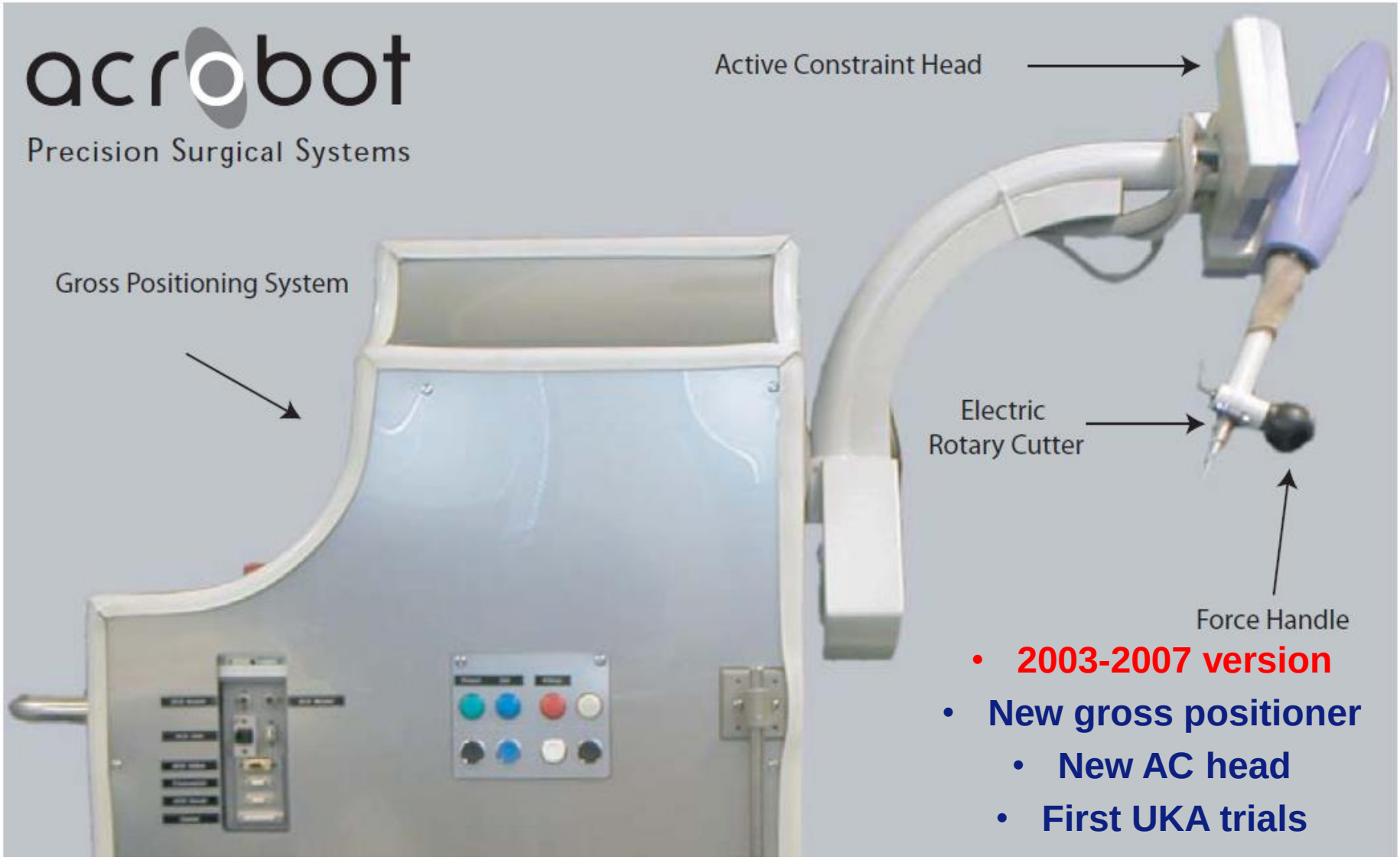




FIRST FUNDING…
TECHNOLOGICAL PROBLEMS

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

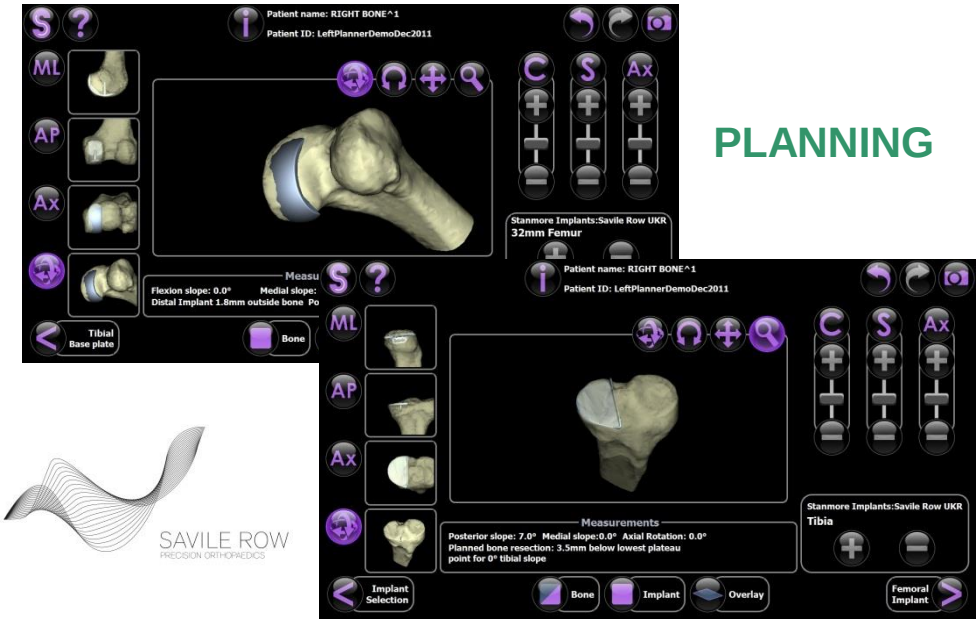
- **New body frame**
- **New graphical front end**
- **First commercial UKA system**

FIRST MAJOUR ACQUISITION ➔ EXCITING OUTLOOK

Remote Centre Mechanism (RCM)

Now and Then…

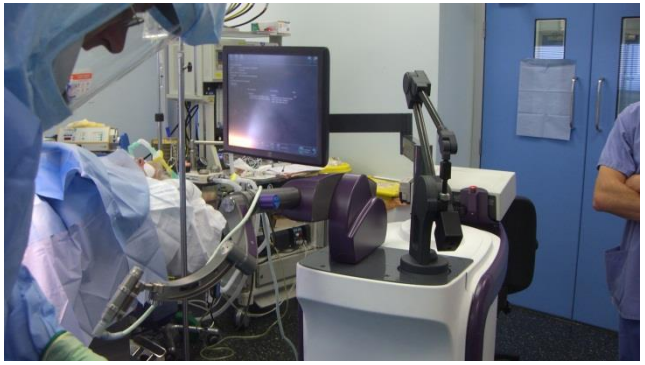
"Savile Row™" System:



PLANNING

MANUFACTURE

IMPLANTATION



- **Customised planning, manufacture and implantation…**

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Now and Then…

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

SECOND MAJOUR ACQUISITION ➔ **CRITICAL MASS REACHED?**

Now and Then…

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

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

SECOND MAJOUR ACQUISITION ➔ CRITICAL MASS REACHED?

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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

Patient Specific Instruments
(*www.zimmer.com*)

Signature
(www.biomet.com)

My Knee
(www.medacta.com)

iJig
(www.conformis.com)

ShapeMatch
(www.stryker.com)

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

➔ **Doubtful long-term future?**

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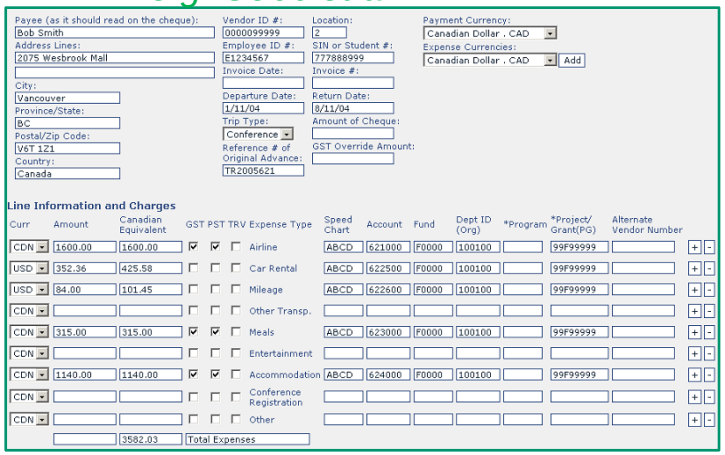
A Glimpse into the Future (with some bias…)

Better Measurement Tools

Personalised web-based tools

e.g. Cobb et al.



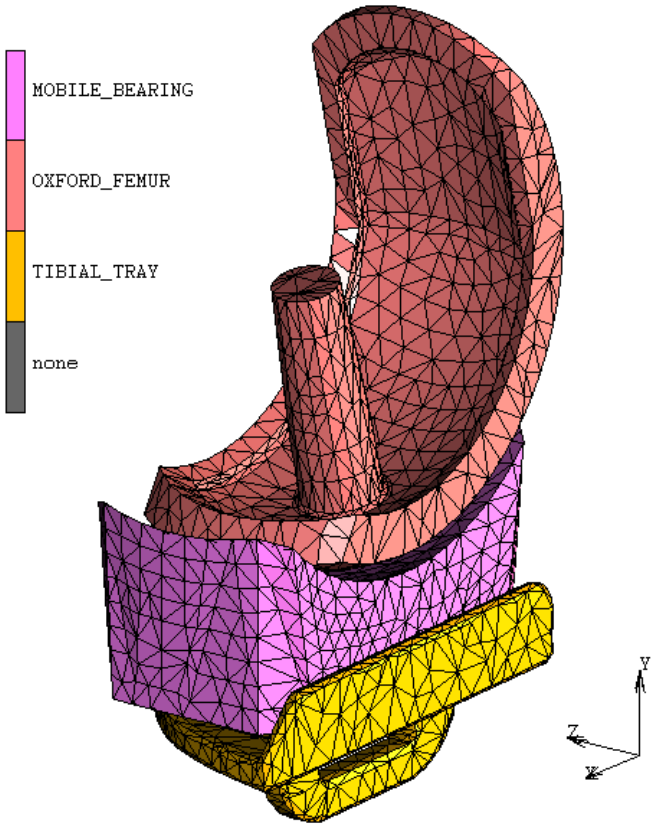
Payee (as it should read on the cheque): Bob Smith
Address Lines: 2075 Wesbrook Mall
City: Vancouver
Province/State: BC
Postal/Zip Code: V6T 1Z1
Country: Canada
Vendor ID #: 0000099999
Employee ID #: E1234567
Invoice Date:
Departure Date: 1/11/04
Trip Type: Conference
Reference # of Original Advance: TR2005621
Location: 2
SIN or Student #: 777888999
Invoice #:
Return Date: 8/11/04
Amount of Cheque:
GST Override Amount:
Payment Currency: Canadian Dollar , CAD
Expense Currencies: Canadian Dollar , CAD — Add

Line Information and Charges

Curr	Amount	Canadian Equivalent	GST	PST	TRV	Expense Type	Speed Chart	Account	Fund	Dept ID (Org)	*Program	*Project/ Grant(PG)	Alternate Vendor Number
CDN	1600.00	1600.00	☑	☑	☐	Airline	ABCD	621000	F0000	100100		99F99999	
USD	352.36	425.58	☐	☐	☐	Car Rental	ABCD	622500	F0000	100100		99F99999	
USD	84.00	101.45	☐	☐	☐	Mileage	ABCD	622600	F0000	100100		99F99999	
CDN			☐	☐	☐	Other Transp.							
CDN	315.00	315.00	☑	☑	☐	Meals	ABCD	623000	F0000	100100		99F99999	
CDN			☐	☐	☐	Entertainment							
CDN	1140.00	1140.00	☑	☑	☐	Accommodation	ABCD	624000	F0000	100100		99F99999	
CDN			☐	☐	☐	Conference Registration							
CDN			☐	☐	☐	Other							
		3582.03	Total Expenses										

Modelling and simulation

e.g. Hopkins et al.



Pictures courtesy of
Dr Andrew Hopkins, Zimmer Orthopaedics

New sensing for diagnostics & assessment

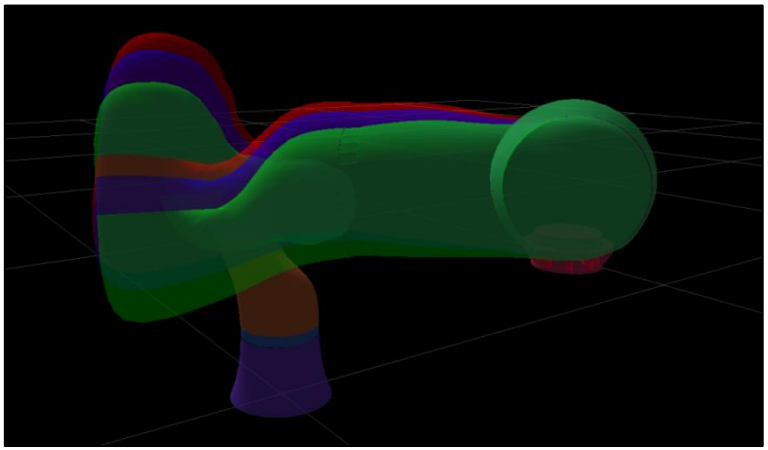
e.g. Nathwani et al.

eAR®, Imperial College, Nathwani et al.

Better Technology Integration

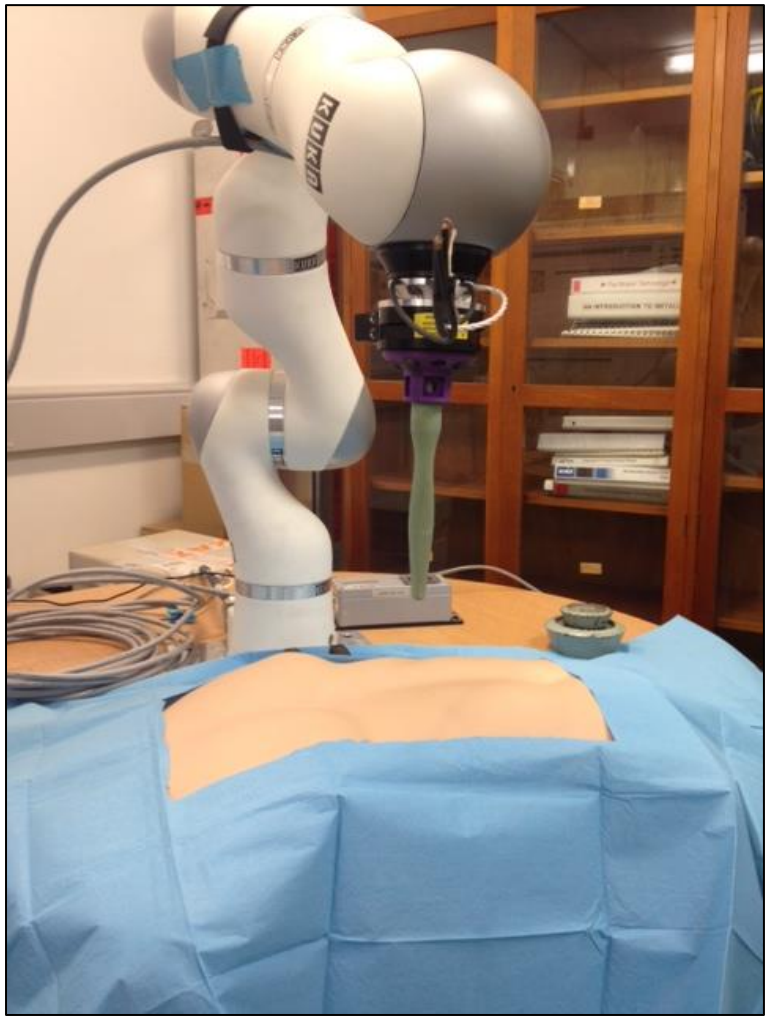
Courtesy of Dräger Medical AG & Co. KG

Hands-On Systems & Natural Motion



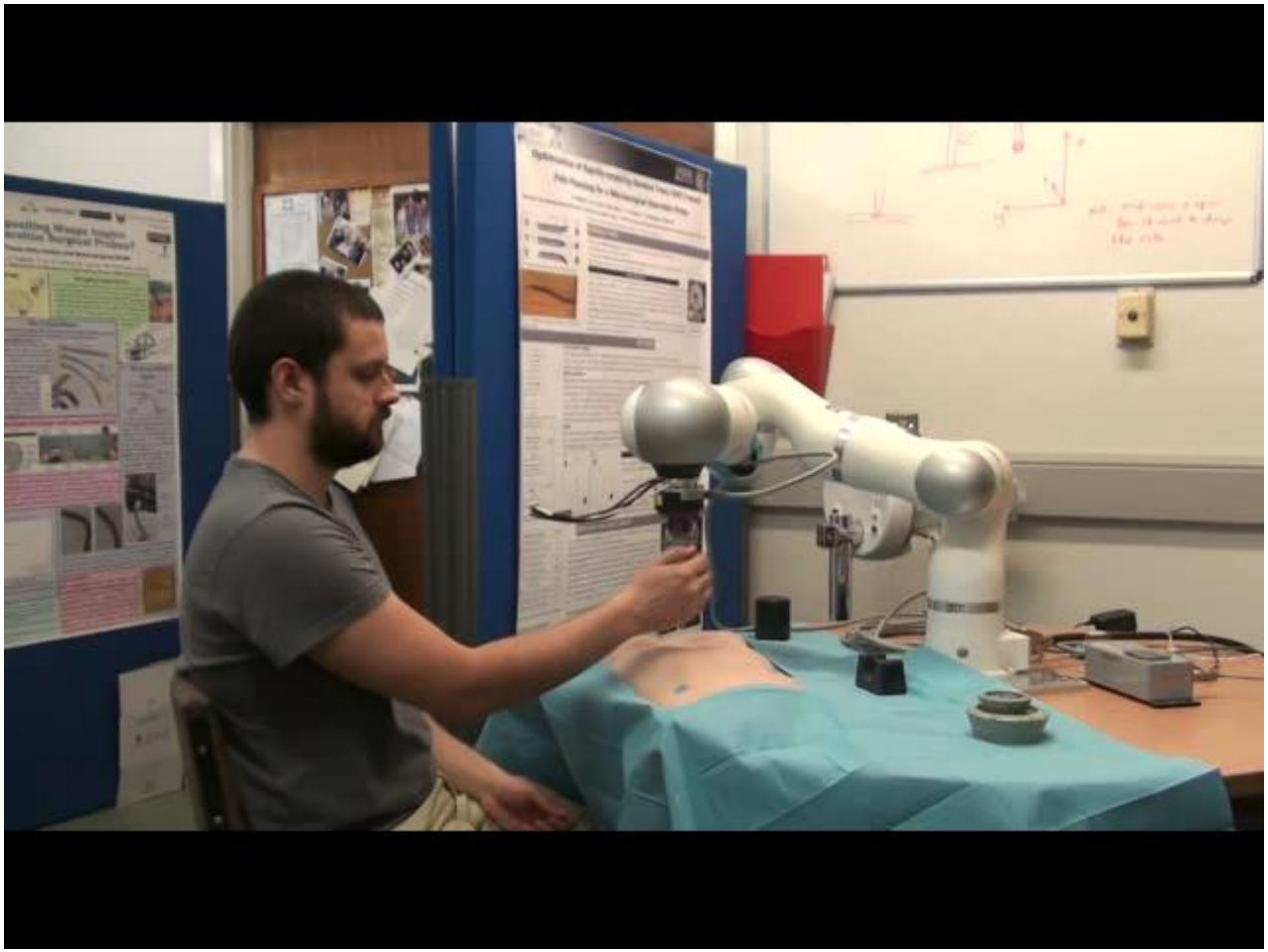
- There are many benefits to hands-on robotic surgery
- However, the surgeon must also interact with the end effector dynamics
- Redundant robots can achieve a pose in an infinite number of ways

Hands-On Systems & Natural Motion



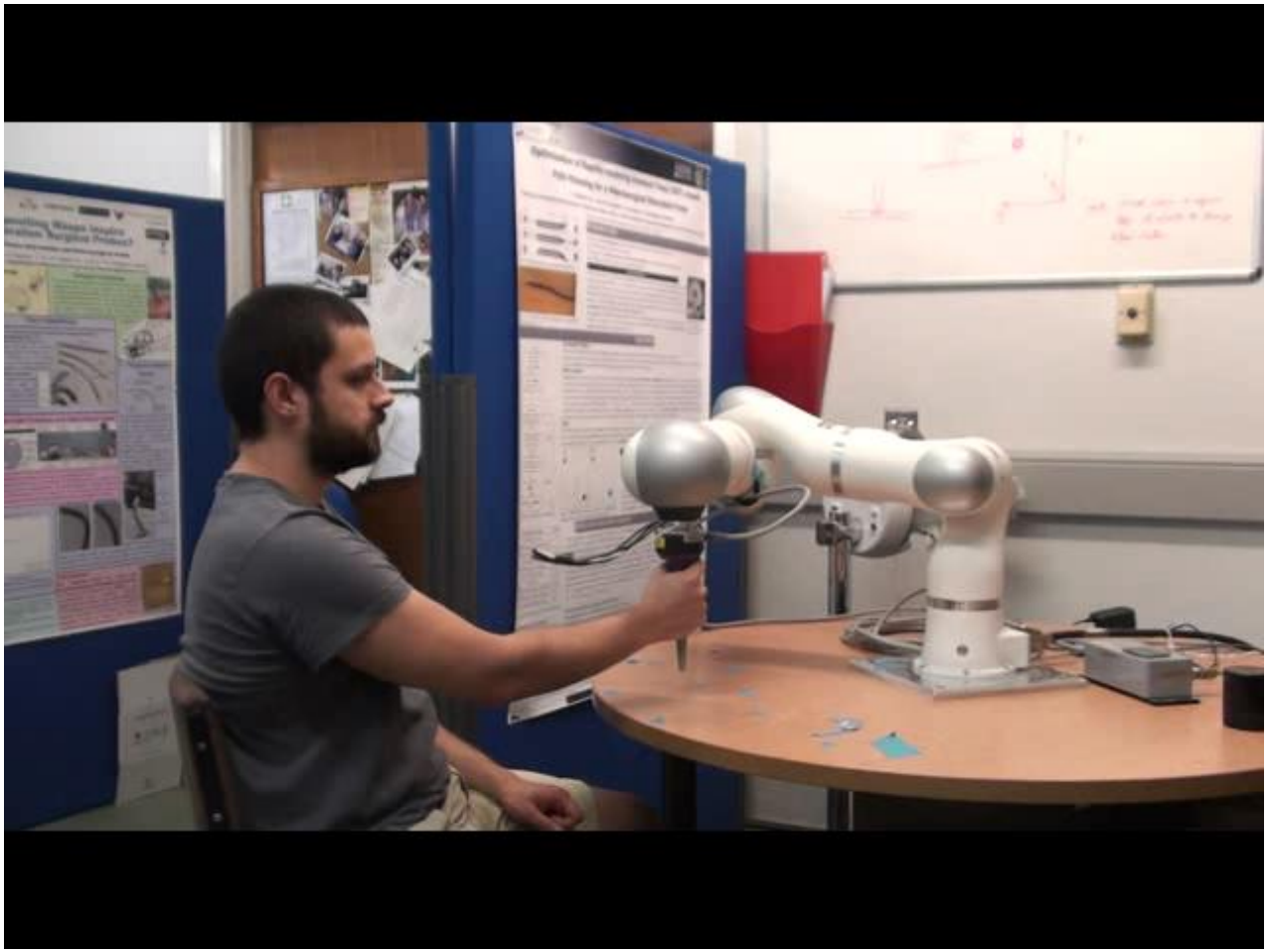
- Null-space optimization creates a more natural feeling without affecting the surgeon's pose
- End effector mass and friction optimization demonstrated on the **Kuka LWR 4+**

Hands-On Systems & Natural Motion



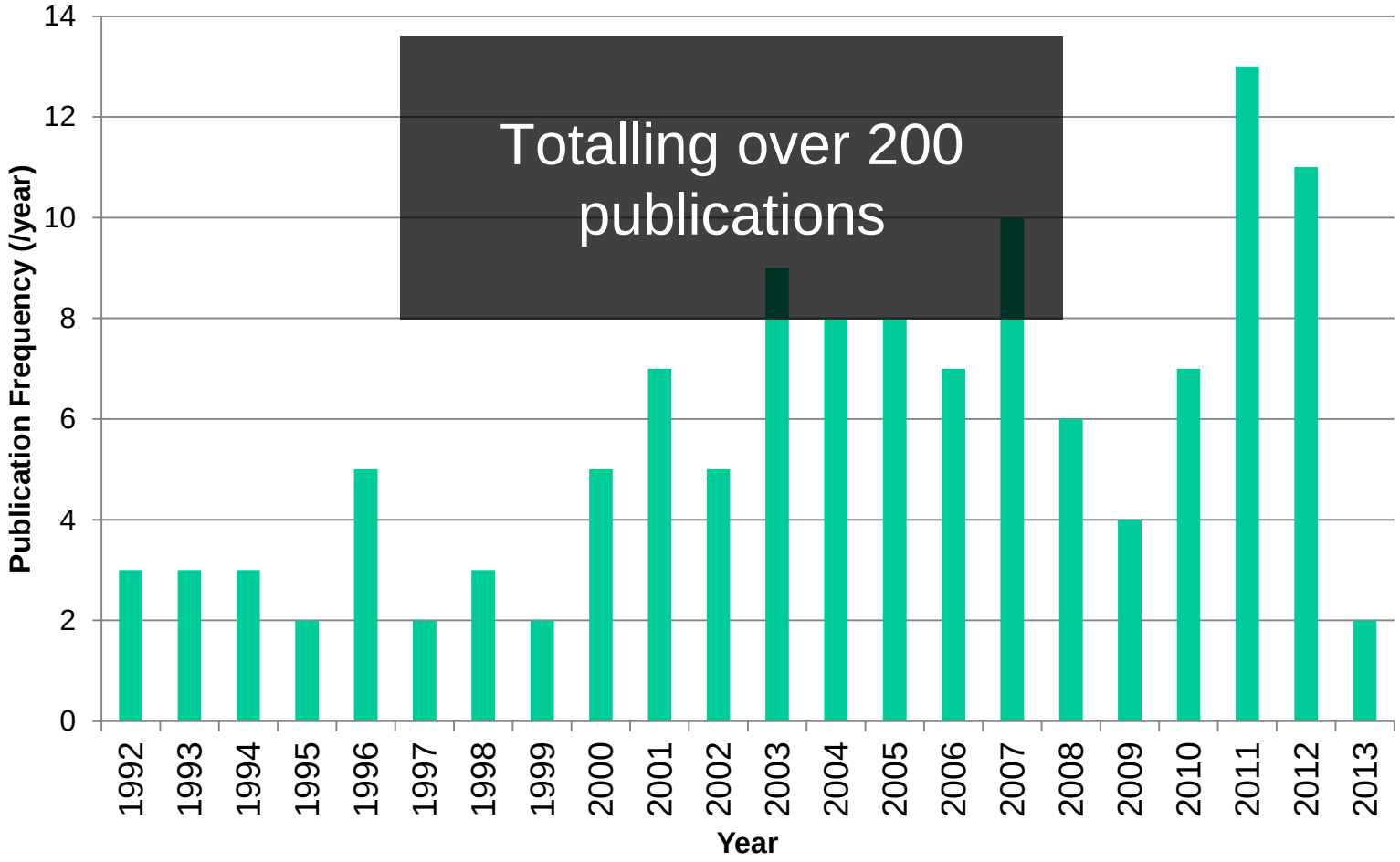
Petersen and Rodriguez y Baena "Mass and Inertia Optimization for Natural Motion in Hands-On Robotic Surgery" (IROS 2014)

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

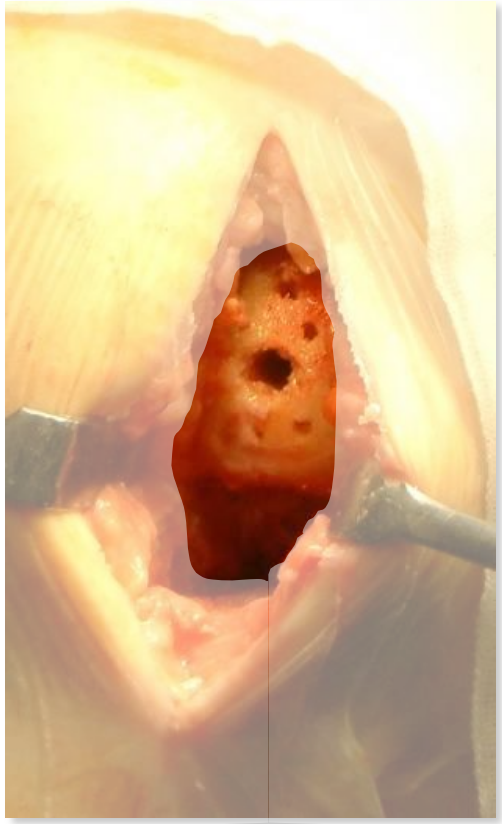


Bowyer and Rodriguez y Baena 'Active constraints in unstructured environments'
(Workshop on cooperative control, Hamlyn Symposium 2013)

Future Trends

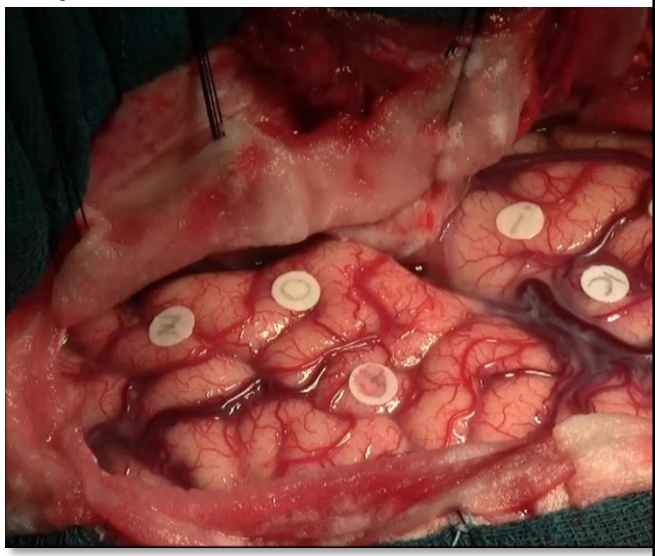
Active constraints

(Rigid, structured environments)



Dynamic active const

(Deformable, unstructured e



The Hidden Problem behind ACs

Dynamic Frictional Constraints

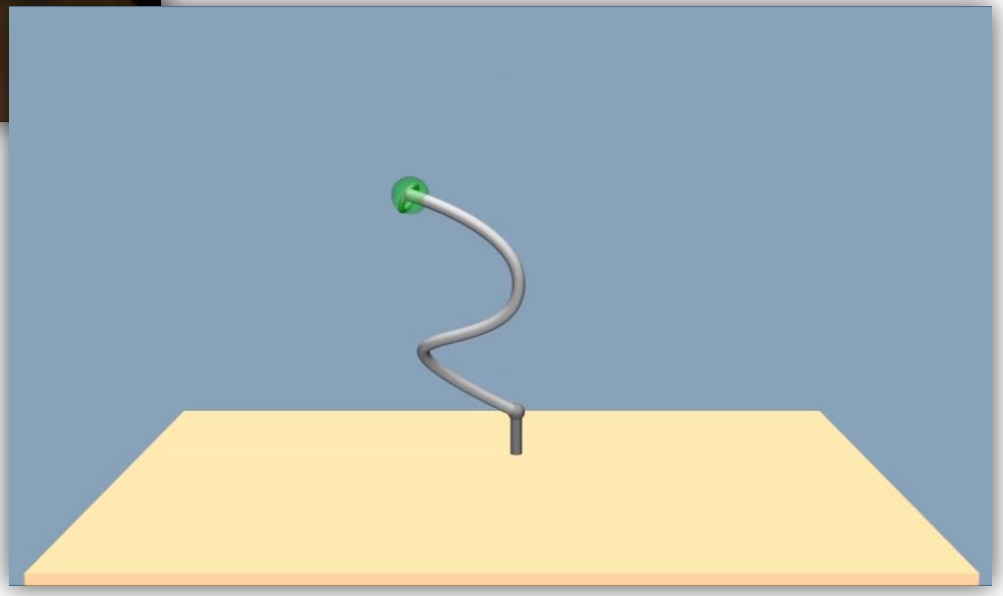
https://fatsmokermma.files.wordpress.com/2013/01/judo-kevin-murphy.jpg

Dynamic Frictional Constraints

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

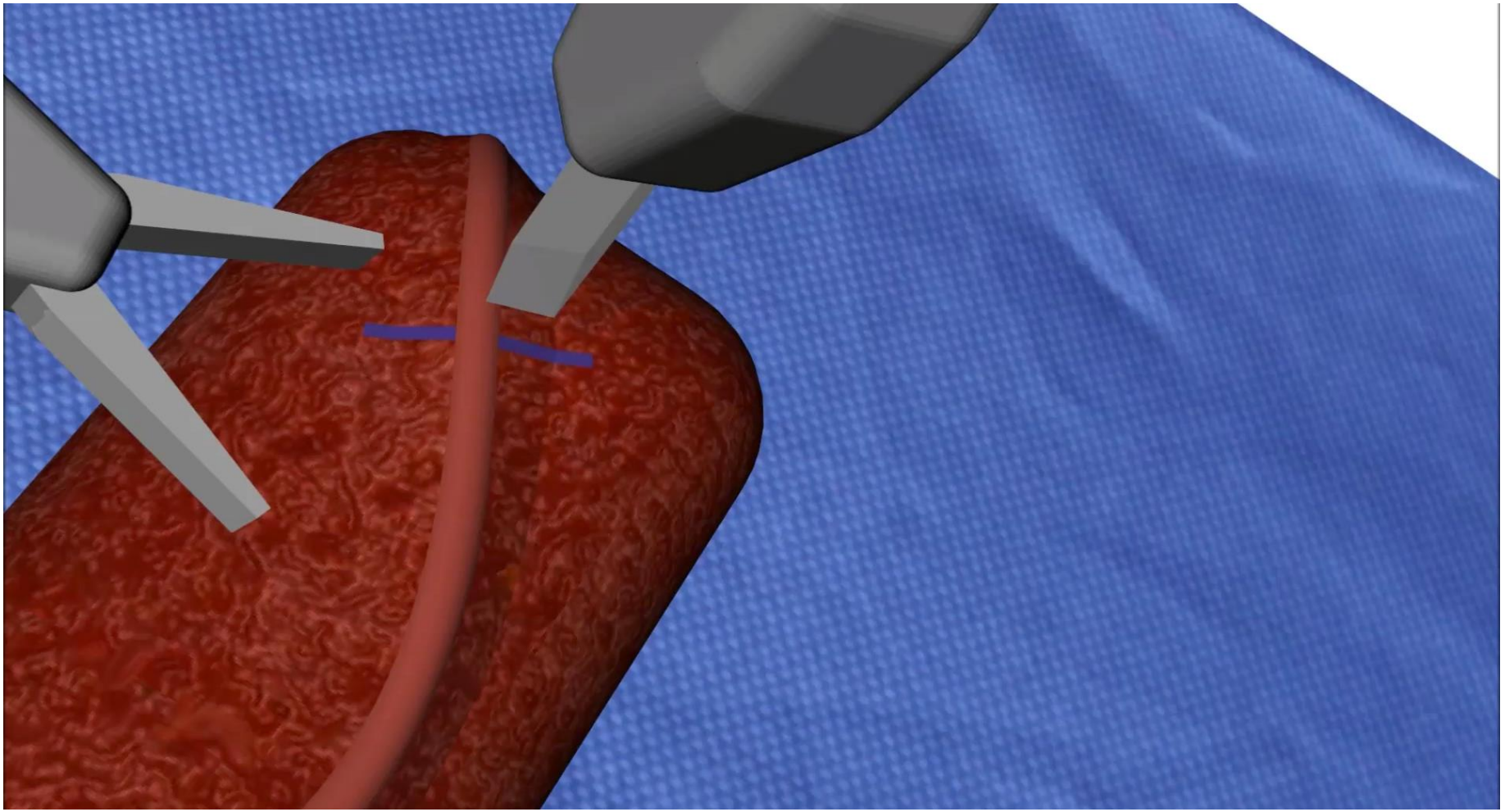
3D

6D



Bowyer and Rodriguez y Baena "Dynamic frictional constraints in rotation and translation" (ICRA 2014)

A Glimpse into the Future of ACs?



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Dr Matthew Oldfield
Dr Hadi El Daou

Key Collaborators

Justin Cobb (orthopedics)
Nandi Dasgupta (neurosurgery)

SEVENTH FRAMEWORK PROGRAMME

EPSRC
Engineering and Physical Sciences Research Council

NHS
National Institute for Health Research

erc

British Heart Foundation

Imperial College London

Imperial College London

Thank you.