Introduction to Medical Robotics

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Medical Robotics =

Robotics to assist doctors / surgeons

Assistive technologies

Robots and machines that improve the quality of life of disabled and elderly people, mainly by increasing personal independence

Robotics for surgery, exploration, diagnosis, therapy...

Rehabilitation robotics

Robots and mechatronic tools for clinical therapy in neuro-motor rehabilitation, training…

Robotics to assist people

Outline

- A short overview on assistive technologies & rehabilitation robotics
- A more detailed introduction to surgical robotics

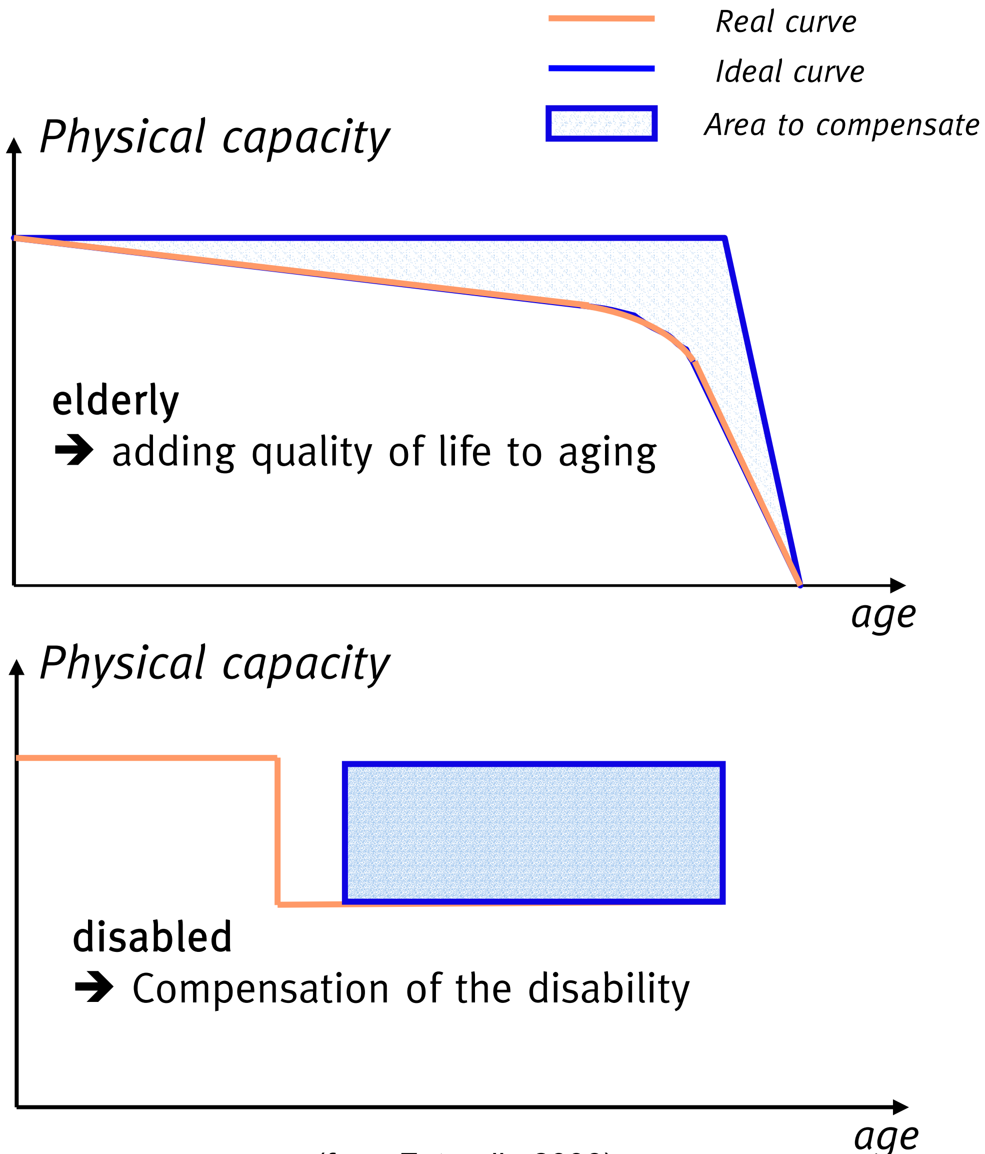
Assistive technologies

- **Elderly**
- **Disabled**

Physical capacity along time

1: detect the failing as soon as possible
2: compensate close to the 100% of capacity
3: continue the maximum of capacity as long as possible

Goal of AT: provide tools to improve or restaure physical performance

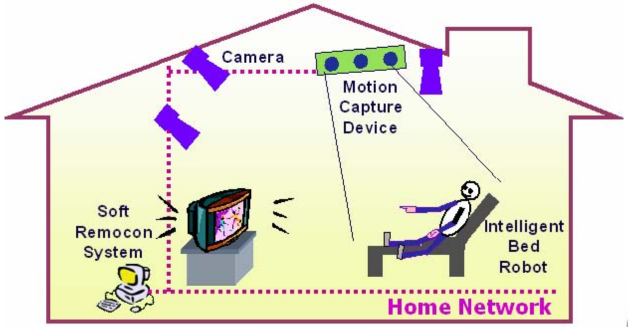


(from Fatronik, 2006)

Assistive technologies

Prothetic devices / Artificial limbs

Smart living spaces



Assistive technologies

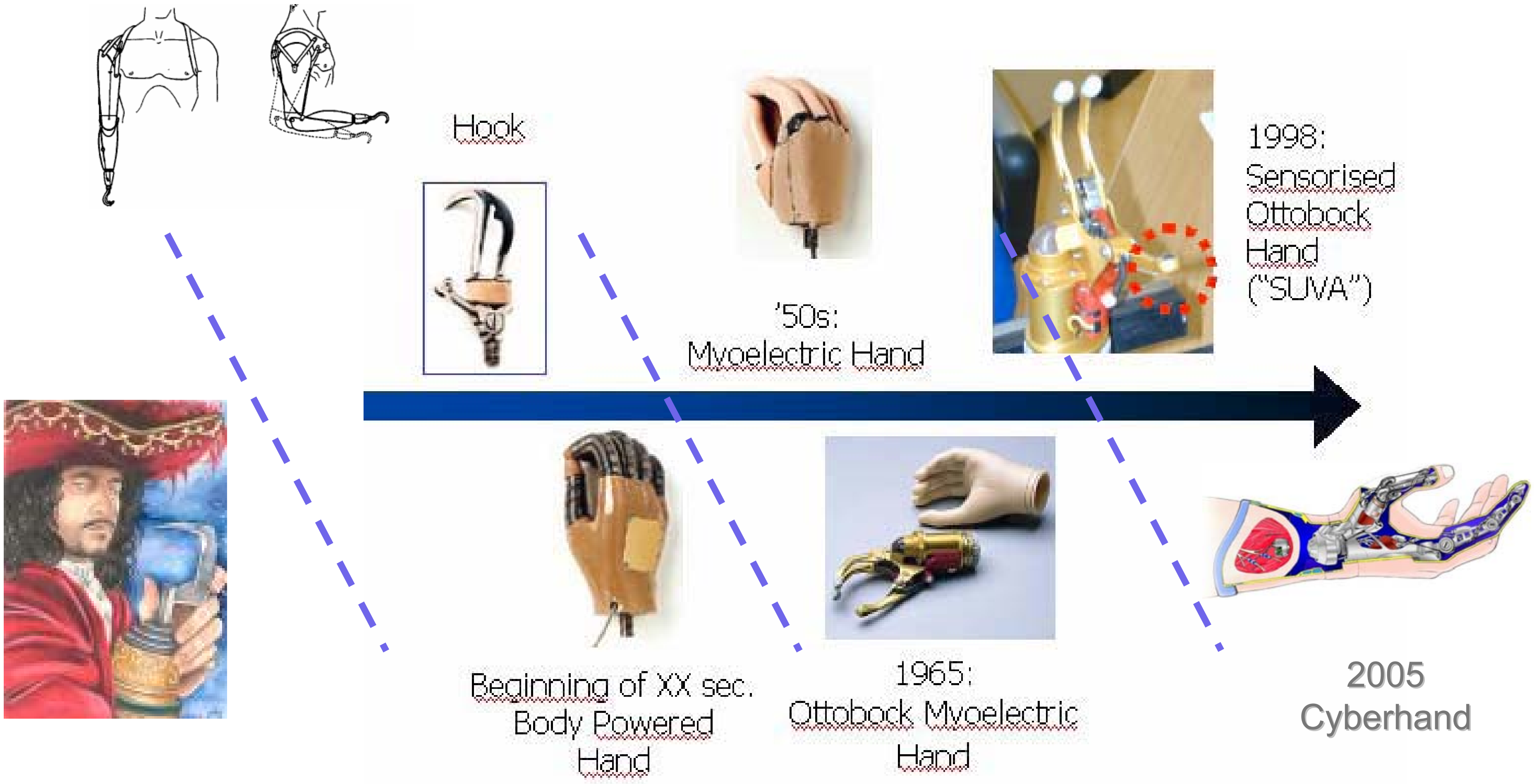
Orthotic devices / Exoskeletons

FES

Personal assistants

Robotic aids

Assistive technologies: prosthetic devices (1/5)



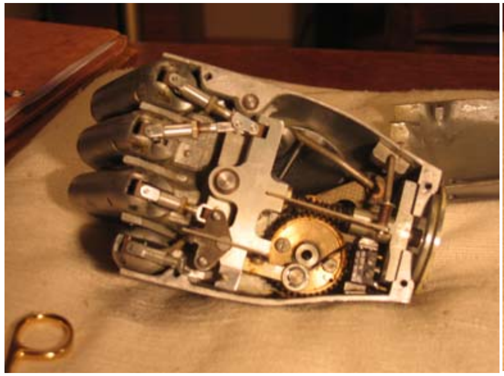
Passive | **Active "body-powered"** | **Active "externally-(motor) powered"** | **Biomecatronics prostheses**

Cosmetic or functional → ***Cosmetic and functional***

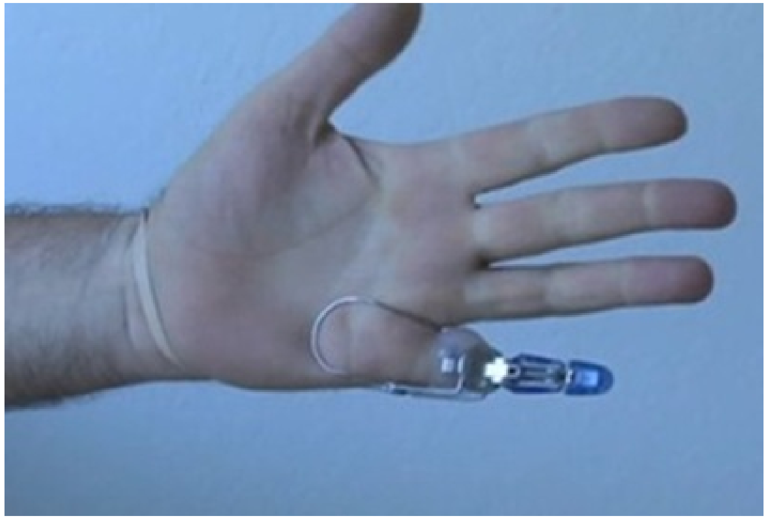
Evolution of the active hand prostheses (revisited from EURON Roadmap, 2004)

Assistive technologies: prosthetic devices (2/5)

Belgrad's Hand (Mihailo Pupin Institute, early 1970)



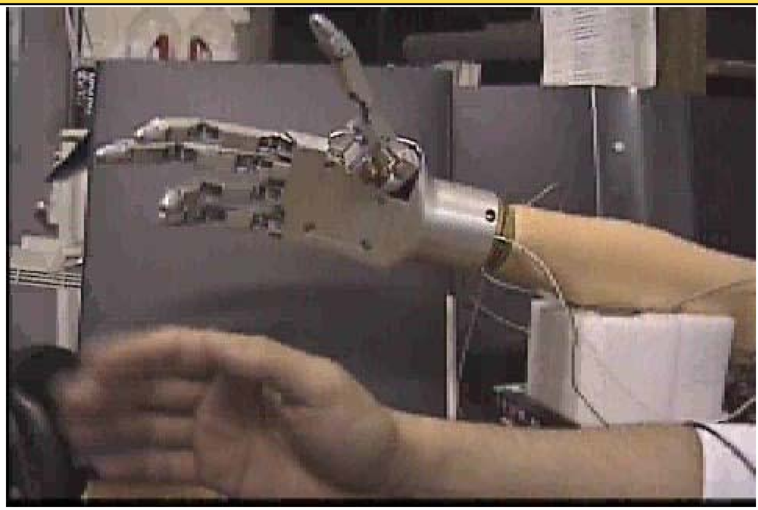
X-Finger (Didrick Medical Inc, Naples, Fl), 2007

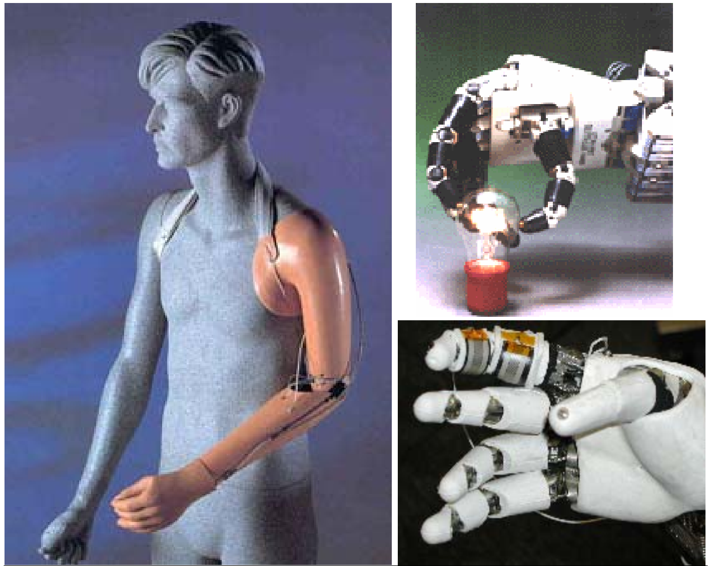


http://www.didrickmedical.com/didrick/index.php?option=com_frontpage&Itemid=1

Assistive technologies: prosthetic devices (3/5)

EMG Prosthetic Hand (Autonomous System Engineering Lab., Japon)





Utah Arm 2, Utah Hand (Motion Control, Inc., USA)

The flexion controlled by an electric motor in combination with a continuous adjustment of the gear
→ Close to natural movement: natural swinging, fast moves, high torques...

Bionic Arm (Otto Bock HealthCare, Inc., USA)

Assistive technologies: prosthetic devices (4/5)

Speed & Patient Adaptive MagnetoRheological Knee Prosthesis (MIT, USA)

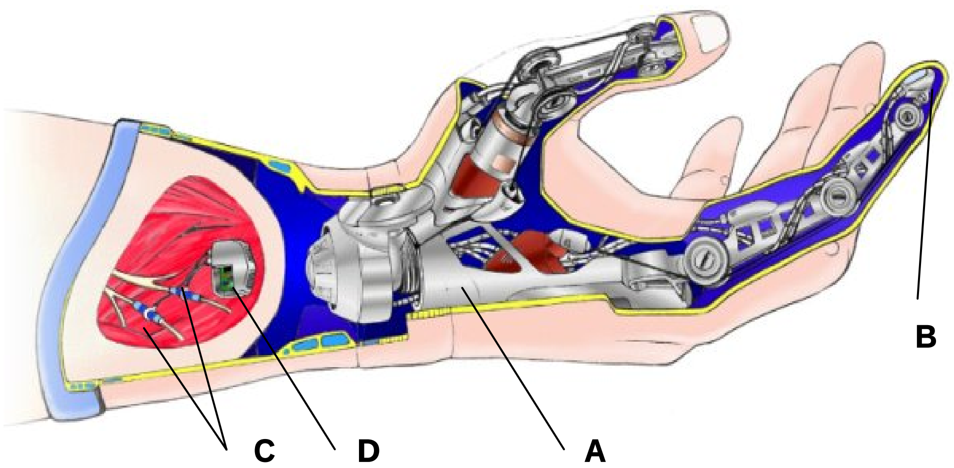
- Local sensing of knee force, torque, and position.
- Natural gait with hydraulic swing phase dynamics control:
  - changing speed
  - slopes
  - uneven terrain
  - stairs

Bionic Leg / Power knee (Victhom Human Bionics, Québec)

C-Leg (Otto Bock HealthCare, Inc., USA)

Assistive technologies : prosthetic devices (5/5)

Cyberhand Advanced Prosthetic Hand (EU Project coordinated by SSSA, Pisa)



(A) advanced underactuated multi-degree of freedom hand
(B) finger tip pressure built-in sensors
(C) neuroprosthetic electrodes implanted in or around the nerve stump to detect the user's volitional commands and to feedback sensations from the pressure sensors (and others)
(D) implanted custom stimulator/amplifier

- Neurobotics / Robionics / Biomecatronics prostheses : interfaces between an assistive device and the human nervous system such that the user's brain functions become part of the system control loop
- R&D issues
  - biocompatible implantable micro-sensors and electrodes
  - Neurophysiology: which neurons to interface?
  - Data processing (volitional command and artificial sensory feedback)…

Courtesy of Ken Yoshida, ROBEA, March 30,2005

Assistive technologies: orthotic / wearable devices
(1/2)

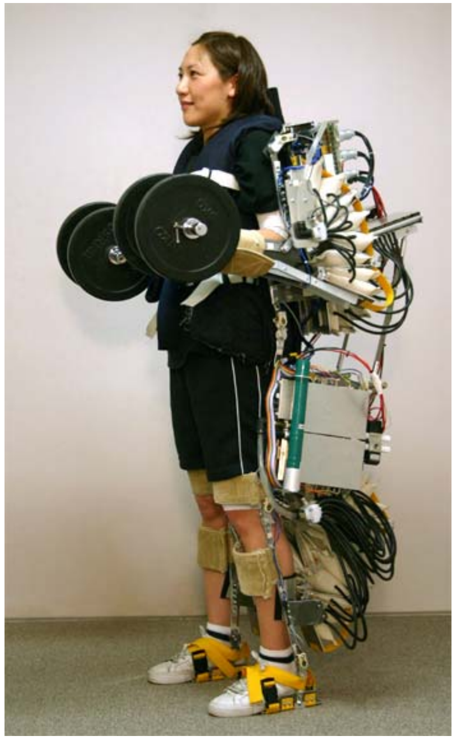
Rancho golden arm (Rancho Los Amigos Hosp., Downey), 1970

... a light, wearable brace support suit which comprises DC motors at the joints, rechargeable batteries, an array of sensors and a computer-based control system. It is fitted on the body and worn underneath the clothing

ReWalk (Argo Medical Technologies Ltd./ Technion, Israel), 2007

Assistive technologies: orthotic / wearable devices (2/2)

Orthoses to compensate for disability... but also to extend the human strength



Power suit: allows a nurse to carry a 85-kg patient (Kanagawa Institute of Tech., Atsugi, Japan)

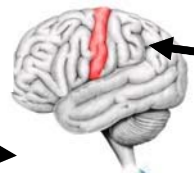
The Berkeley Lower Extremity Exoskeleton (BLEEX) (Univ.of Berkeley, USA), 2004

- R&D issues
  - Miniaturization of actuators and batteries
  - Force control & haptics
  - Safety…

Assistive technologies: Functional Electro-Stimulation (FES) (1/4)

Cochlear implant

HiResolution (Advanced Bionics)
Digisonic (MXM, France)
1980



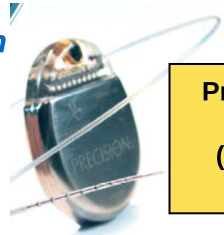
Deep brain stimulation (Parkinson, TOC, depression...)

DBS leads
(Medtronics)
1990

Pacemaker

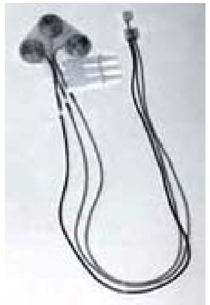
ELA Medical,
Medtronics…
1950

Chronic pain therapy



Precision Spinal Cord
Stimulation
(Advanced Bionics)
1960

Bladder control

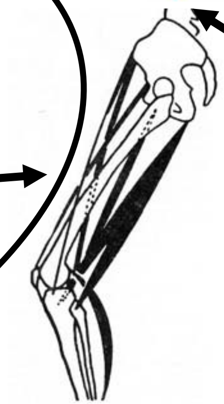


Finetech-Brindley Bladder
System (Finetech Medical)
1980

- *Palliative solution for movement deficiencies*

  ➔ *FES (1960)*

Movement

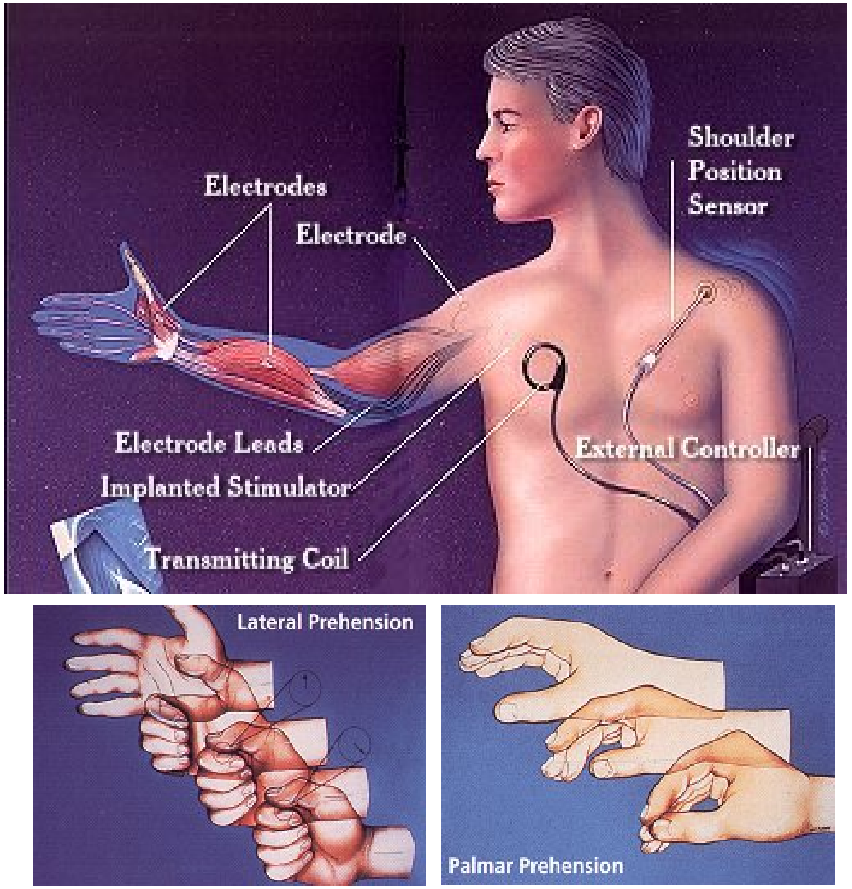


- *New therapies for enhancing recovery of sensory-motor functions*

  ➔ *FET (D. Popovic, 2000)*

www.ifess.org

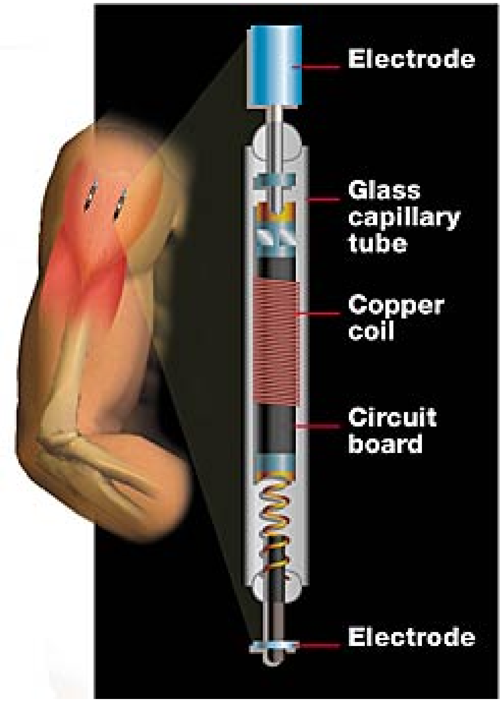
Assistive technologies: Functional Electro-Stimulation (FES) (2/4)



Freehand system (NeuroControl Corp., Cleveland, Ohio, USA)

Out of business

BION (Alfred E. Mann Institute, USC, Los Angeles), 1988

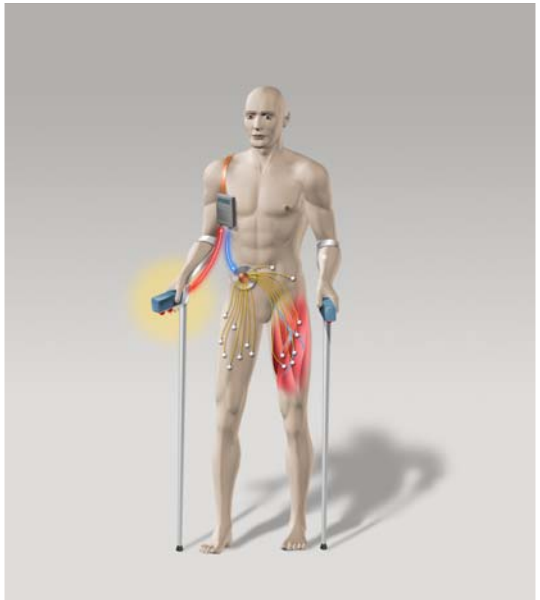


Still a prototype

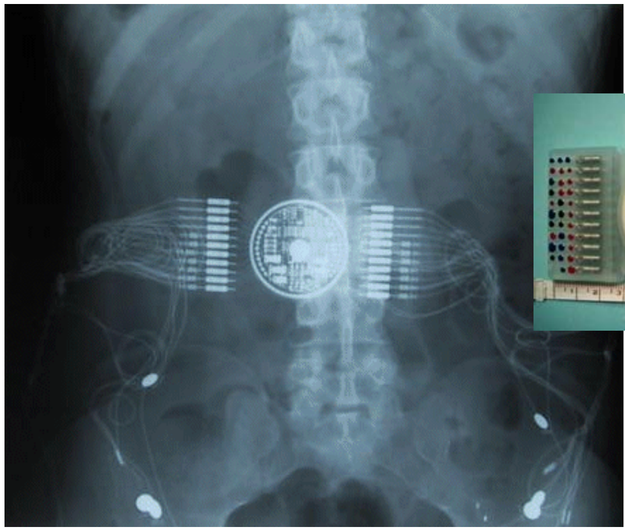
On the shelves

Drop Foot Stimulator (Finetech Medical, Hets, UK)

Assistive technologies: Functional Electro-Stimulation (FES) (3/4)



SUAW, EU-Project, (Coordinated by Prof. Rabischong, Montpellier), 1996-2000



Partial restoration of the locomotion function in certain paraplegic patients

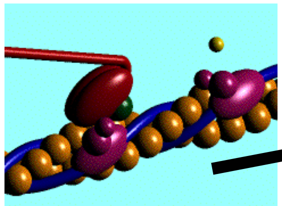
LIRMM

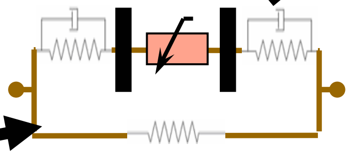
Assistive technologies: Functional Electro-Stimulation (FES) (4/4)

DEMAR Project (LIRMM-INRIA-Montpellier, MXM-Valauris, SMI-Aalborg, Centres Propara, Bouffard-Vercelli), 2003-…

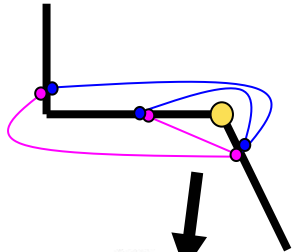
➔ To produce more natural movement and to minimize fatigue

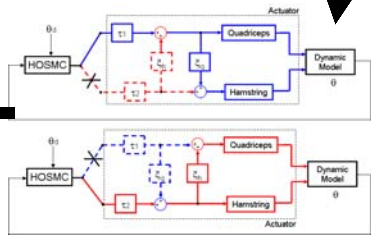
- Modeling & identification of the neuro-muscular system
- Synthesis of stimulation patterns
- High level coordination and robust control of movement
- Interfacing artificial and natural parts through neuroprosthetic devices:
  - Stimulation: distributed electrodes, RF link
  - Sensing: ENG

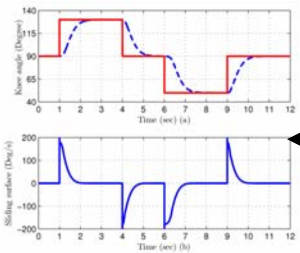


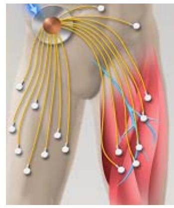


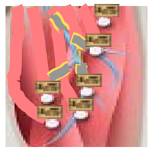
$$\begin{cases} \dot{k}_c = \left(s_0 \alpha k_m - s_u k_c + s_v q \dfrac{s_0 \alpha \sigma_m k_c - s_u \sigma_c k_c}{1 + p k_c - s_v q \sigma_c}\right) u - \dfrac{s_v a k_c}{1 + p k_c - s_v q \sigma_c} \dot{\varepsilon} \\ \dot{\sigma}_c = \dfrac{s_0 \alpha \sigma_m - s_u \sigma_c}{1 + p k_c - s_v q \sigma_c} u + \dfrac{b k_c - s_v a \sigma_c}{1 + p k_c - s_v q \sigma_c} \dot{\varepsilon} \end{cases}$$

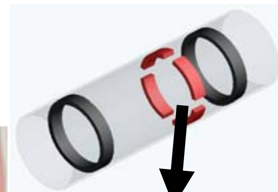


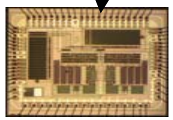












ASIC

http://www-sop.inria.fr/demar/

Assistive technologies:
Robotic mobility / manipulation aids

Robot MANUS (Exact Dynamics BV, The Netherlands)

Care-O-Bot (IPA, Stuttgart)

Assistant to elderly

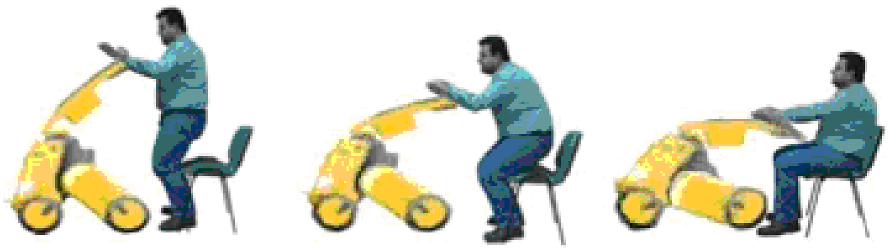
Smart walker GUIDO (Haptica, Dublin, + Univ. Polytech. Madrid)

Physical weight support, steered by the user, with assistance to avoid obstacles

- R&D issues
  - robust indoor navigation
  - natural language interfaces
  - Cost, adaptation to patient
  - Acceptability…

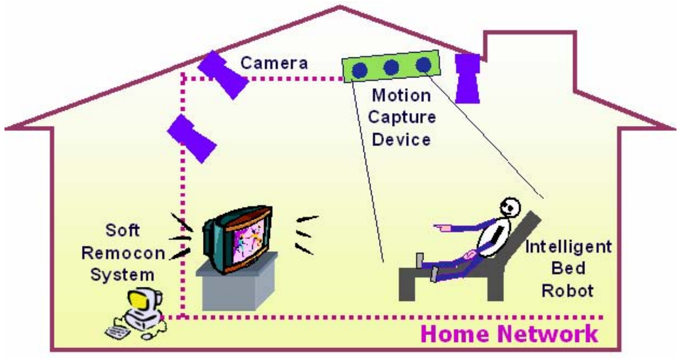
MOVAID EU project (Coordinated by SSSA, Italy)

MONIMAD (Robosoft, LRP, France)



Assistive technologies: Smart living spaces

- To allow persons with chronic physical / cognitive disabilities, namely elderly and disabled, to stay home and live by themselves
- "Intelligence" built in appliances
- Number of sensors embedded in the environment or worn by the person:
  - To anticipate the person needs and intentions
  - For monitoring and diagnosis by off-site persons (cardiac and respiratory cycles, arterial pressure, temperature, motion detectors…)



Intelligent Sweet Home (KAIST, Daejeon, Korea)

- Issues
  - Wireless technologies
  - Pervasive computing
  - Miniature and wearable sensors to measure physiological parameters
  - Human movement / behavior interpretation (speech, facial expression, gestures…)

D.H. Stefanov, Z. Bien, W.C. Bang, Smart house for older persons and persons with physical disabilities: structure, technology, arrangments, and perspectives, IEEE Trans. on Neural Systems and Rehabilitation Engng., Vol. 12(2), June 2004, pp. 228-250.

Assistive technologies: Personal assistants (1/2)

- Healthcare through robots-pets and humanoids
- Robot-pets interact with human beings to make them feel emotional attachment
  - Useful to relax, relieve mental stress, and exercise for physical rehabilitation
  - Elderly, chronically ill children…
  - Robot therapy, “Mental commitment robot"

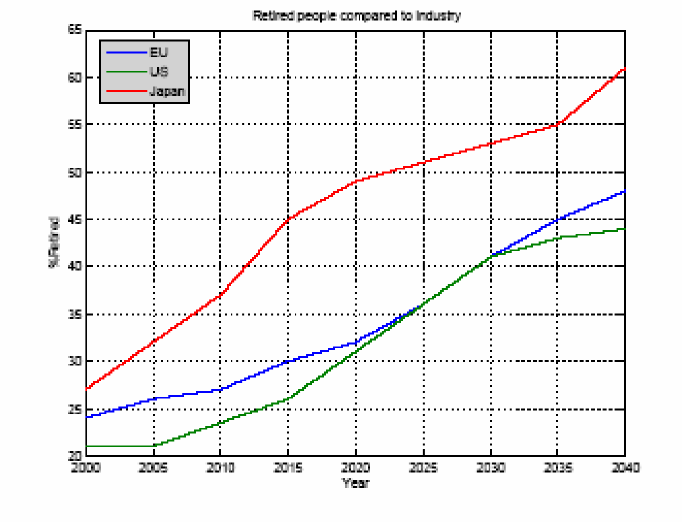
Paro (AIST – Intelligent System Co., Japan)

http://paro.jp/english/

Aibo (Sony, Japan)

Assistive technologies: Personal assistants (2/2)

- Humanoids are supposed to help people in the daily life:
  - assistance in housework
  - entertainment
  - healthcare delivery…



[World Bank, 2004]

- R&D issues: all the research topics of Robotics + Cognitive sciences

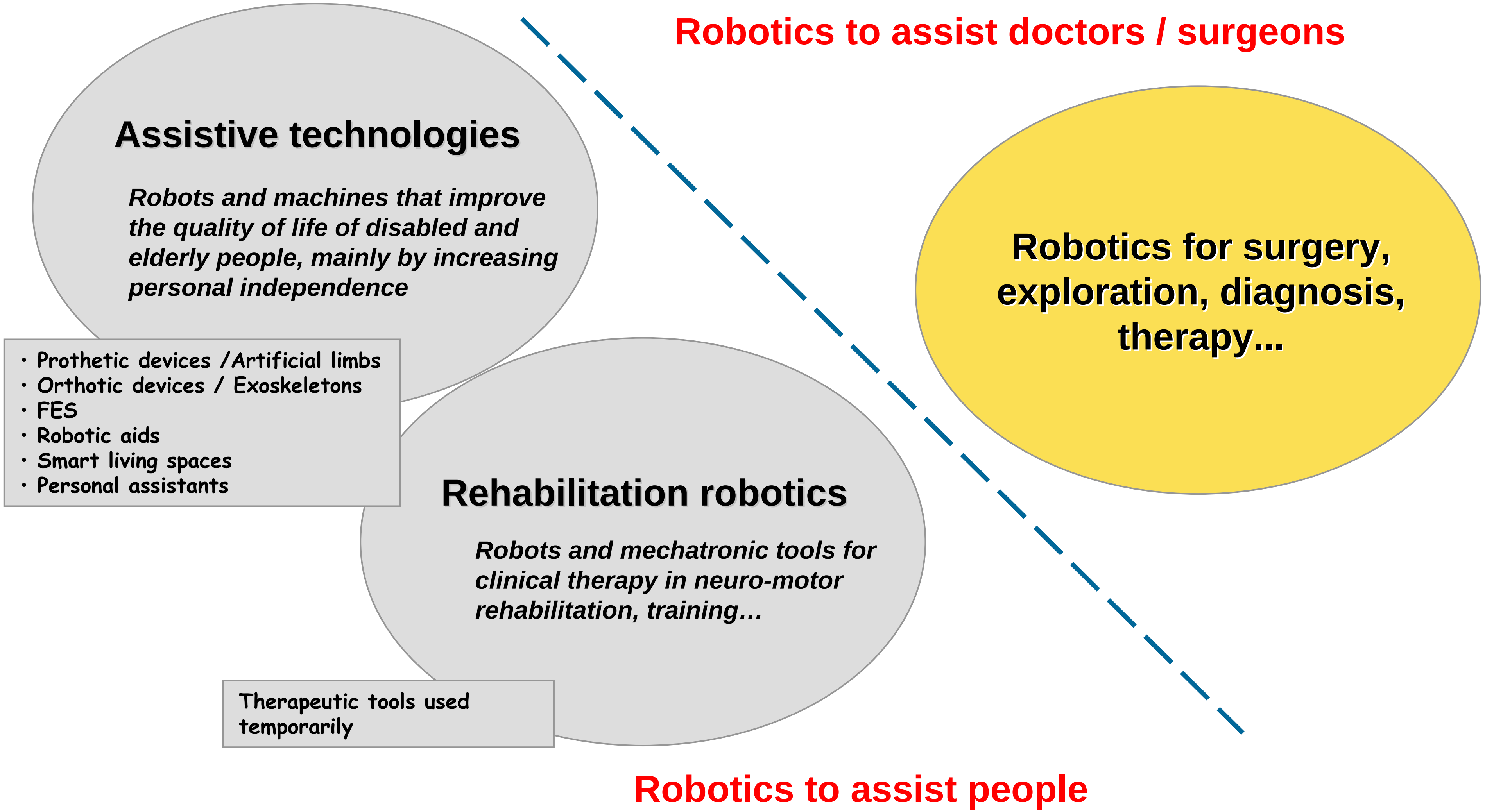
Toyota

Asimo, Honda

VStone

HOAP3, Fujitsu

HRP2, Kawada Industries, Inc. & AIST, Japan


Robotics to assist doctors / surgeons
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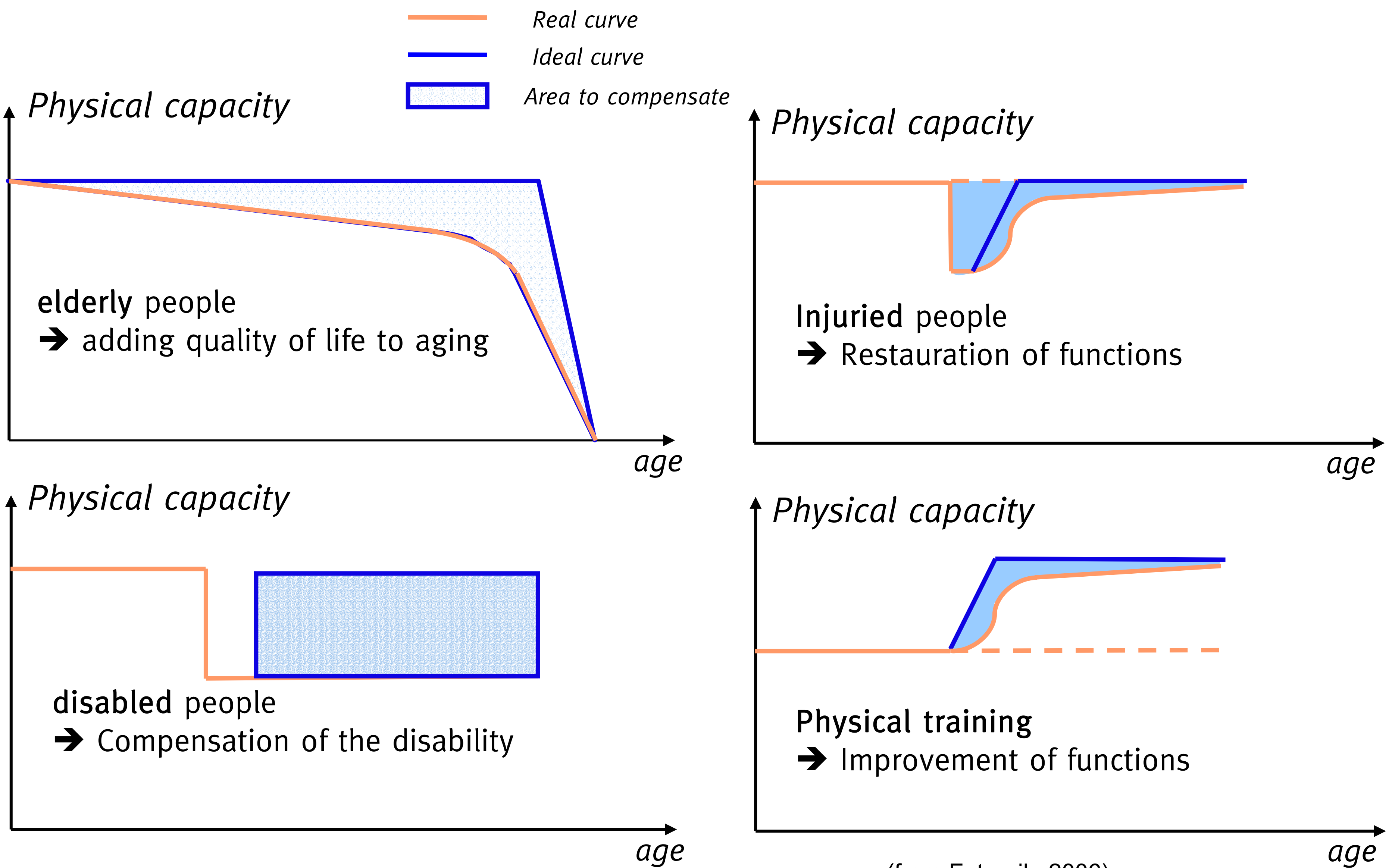
Robots and machines that improve the quality of life of disabled and elderly people, mainly by increasing personal independence
• Prothetic devices /Artificial limbs
• Orthotic devices / Exoskeletons
• FES
• Robotic aids
• Smart living spaces
• Personal assistants
Robotics for surgery, exploration, diagnosis, therapy…
Rehabilitation robotics
Robots and mechatronic tools for clinical therapy in neuro-motor rehabilitation, training…
Therapeutic tools used temporarily
Robotics to assist people

Rehabilitation robotics



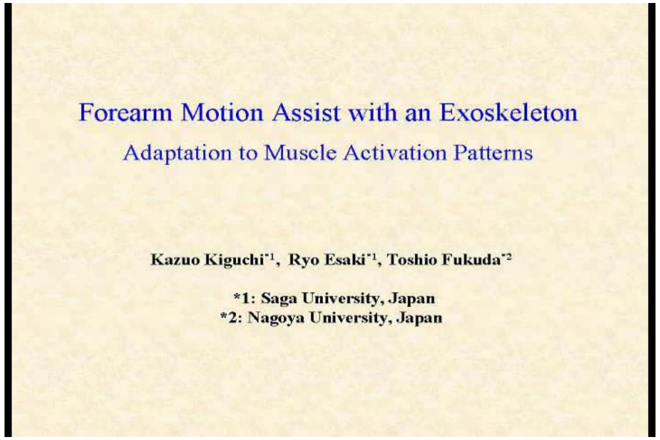
(from Fatronik, 2006)

Rehabilitation robotics

Robotic therapy (Neurobotics Lab, Rob. Institute, Carnegie Mellon, USA)

Virtual environment with a robotic device to extend the strength and mobility of people recovering from strokes

Saga Univ. & Nagoya Univ., Japan



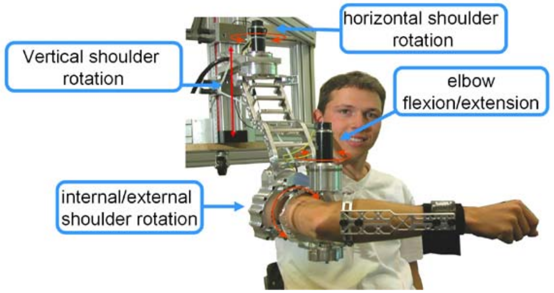
Robotic exerciser: the robot guides the patient through a pre-programmed path. The movement may be performed against a resistance provided by the robot

•Rehabilitation robotics:
robots and mechatronic tools for clinical therapy in neuro-motor rehabilitation

6-dof Rehabilitation Robot Osaka Univ., Japan), 2005

Rehabilitation robotics

Lokomat for gait restauration (Hocoma & ETHZ Zurich, Suisse)



Patient-Cooperative Robot-Aided Rehabilitation for the Upper Extremities Therapy

ARMin (Hocoma & ETHZ Zurich, Suisse)

- R&D issues
  - Better human-robot interfaces
  - FET

Robotics to assist doctors / surgeons

Assistive technologies

Robots and machines that improve the quality of life of disabled and elderly people, mainly by increasing personal independence

- Prothetic devices /Artificial limbs
- Orthotic devices / Exoskeletons
- FES
- Robotic aids
- Smart living spaces
- Personal assistants

Robotics for surgery, exploration, diagnosis, therapy...

Rehabilitation robotics

Robots and mechatronic tools for clinical therapy in neuro-motor rehabilitation, training…

Therapeutic tools used temporarily

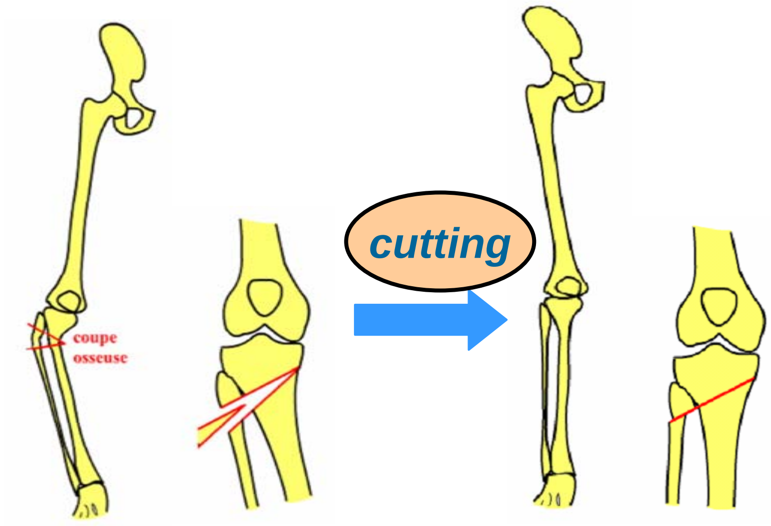
Robotics to assist people

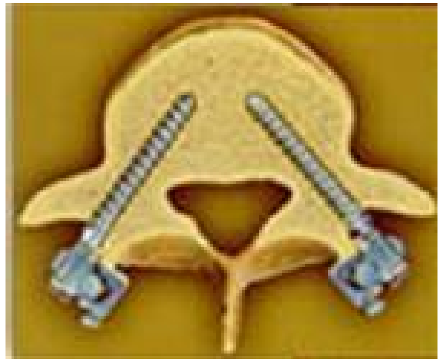
Outline

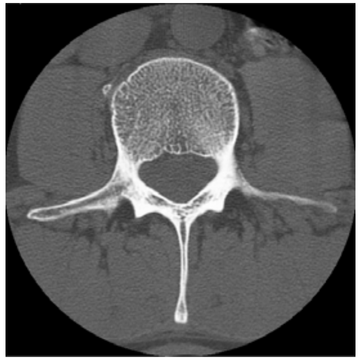
- A short overview on assistive technologies & rehabilitation robotics
- A more detailed introduction to surgical robotics
  - Analysis of some surgical functions and limitations of manual procedures: “Machining”, Constrained manipulation & targeting, Microsurgery
  - State of the art
  - How can robotics help surgery?
  - Future directions of R&D and technical challenges
  - Conclusion
- Biography

Function: "Machining" rigid surfaces (1/2)

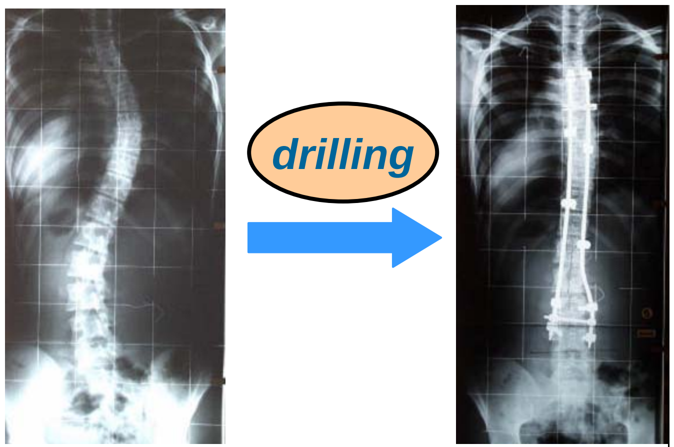
High tibial osteotomy for genu varus (bow-leggedness)

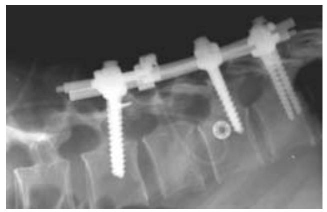






http://www.genou.com/arthrose/osteotomies.htm





Pedicular screw placement to affix rods and plates to the spine

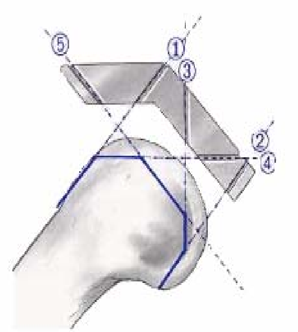
10% to 40% ill-placed screws

(Source J. Troccaz, 1st Summer School in Medical Robotics 2003)

Function: "Machining" rigid surfaces (2/2)

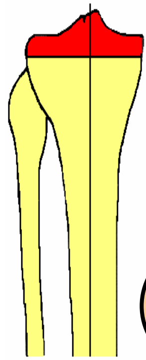
- **Some difficulties:**
  - accurate localization of the cutting planes, drilling axes…,
  - Ligament balance
  - Detection of stiffness changes

Total Knee Arthroplasty (TKA)



Femoral cuts

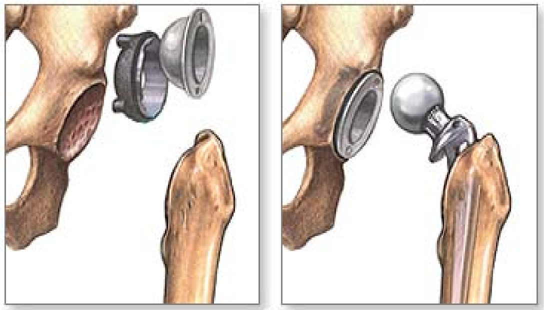
+



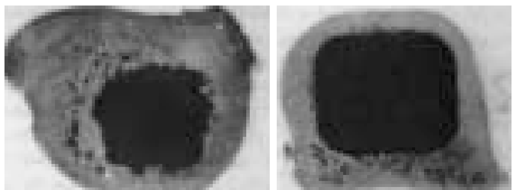
cutting/ milling

Total Hip Arthroplasty (THA)

A metal ball and stem are inserted in the femur and a plastic socket is placed in the enlarged pelvis cup



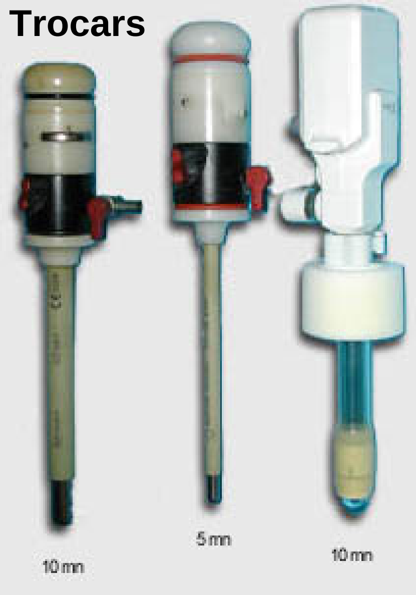
adam.com


Brent, Mittlestadt

milling

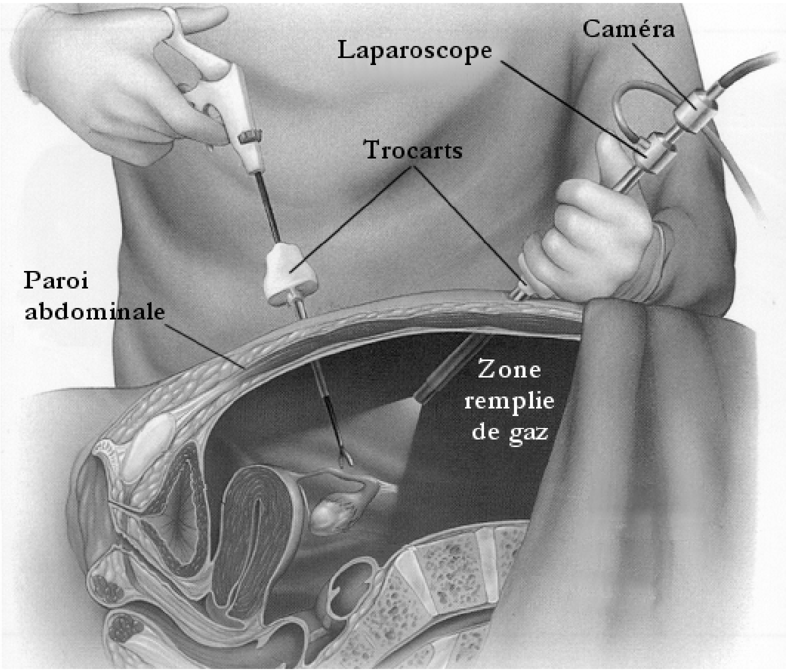
Function: Constrained manipulation (1/2)

Trocars

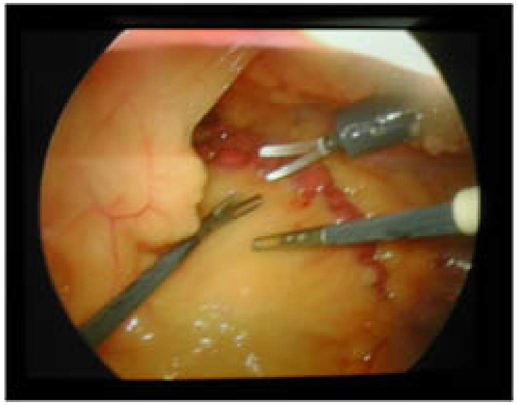


Endoscope + cold light fountain

Minimally-invasive surgery (MIS)



Instruments



Control LCD

Function: Constrained manipulation (2/2)

(Source : US Surgical Corporation)

- Widely used in abdominal surgery, more and more in cardiac surgery

- **Some difficulties:**
  - 3 hands are mandatory
  - monocular vision
  - comfort of the surgeon
  - eye-hand coordination (fulcrum effect)
  - loss of internal mobility due to kinematics constraints induced by the trocar
  - restricted workspace
  - no force feedback (friction in the trocar)
  - occlusion of the field of view
  - compensate for physiological motions
  - avoid critical areas
  - …

Function: Constrained targeting

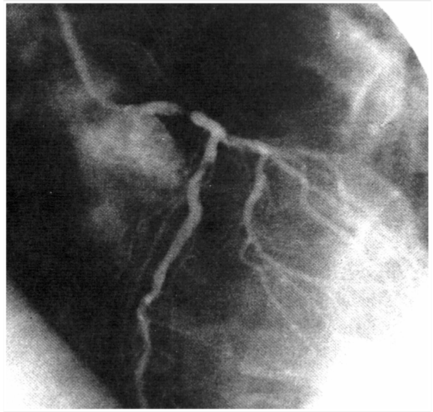
- Interventional radiology: image-guided (CT-scan, MRI) percutaneous therapy / surgery
- Insertion of instruments / needles in soft tissues: biopsy, radio frequency ablation of tumors, cryotherapy; delivery of optimized patterns of local treatments (radiation seeds, injections…)
- Reach smaller and smaller targets
- Wide use in neurosurgery, cardiac surgery, urology, abdominal surgery…

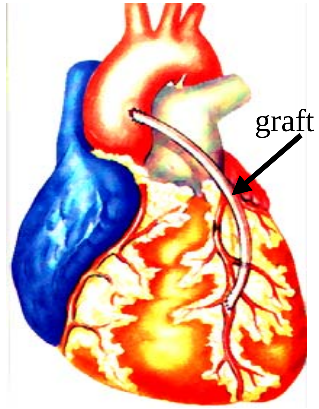
- **Some difficulties:**
  - the surgeon is exposed to radiation
  - requires mental registration of the patient's anatomy to the image in targeting, and precise hand-eye coordination,
  - force control during insertion while penetrating tissues with heterogeneous stiffness
  - compensation for physiological motions
  - Planning to avoid vital areas
  - …

Function: Micro-surgery

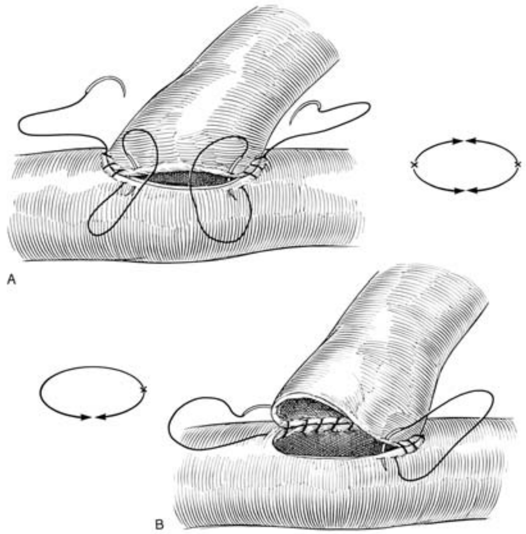
- Example: anastomosis for coronary artery bypass grafting (CABG)
- Ø 2 mm, 10 to 20 penetrations
- Ø of the thread: few tens of μm
- Penetration force: up to 1N
- Resolution: better than 0.1 mm
- suturing (stitching + knot tying),

- **Difficulties:**
  - Requires very accurate position- and force-controlled motion
  - Compensate for physiological movements of the patient
  - Compensate for the natural hand tremor of the surgeon
  - …
  - + the difficulties of MIS if it is done this way





Suturing of the graft to the aorta and the coronary artery

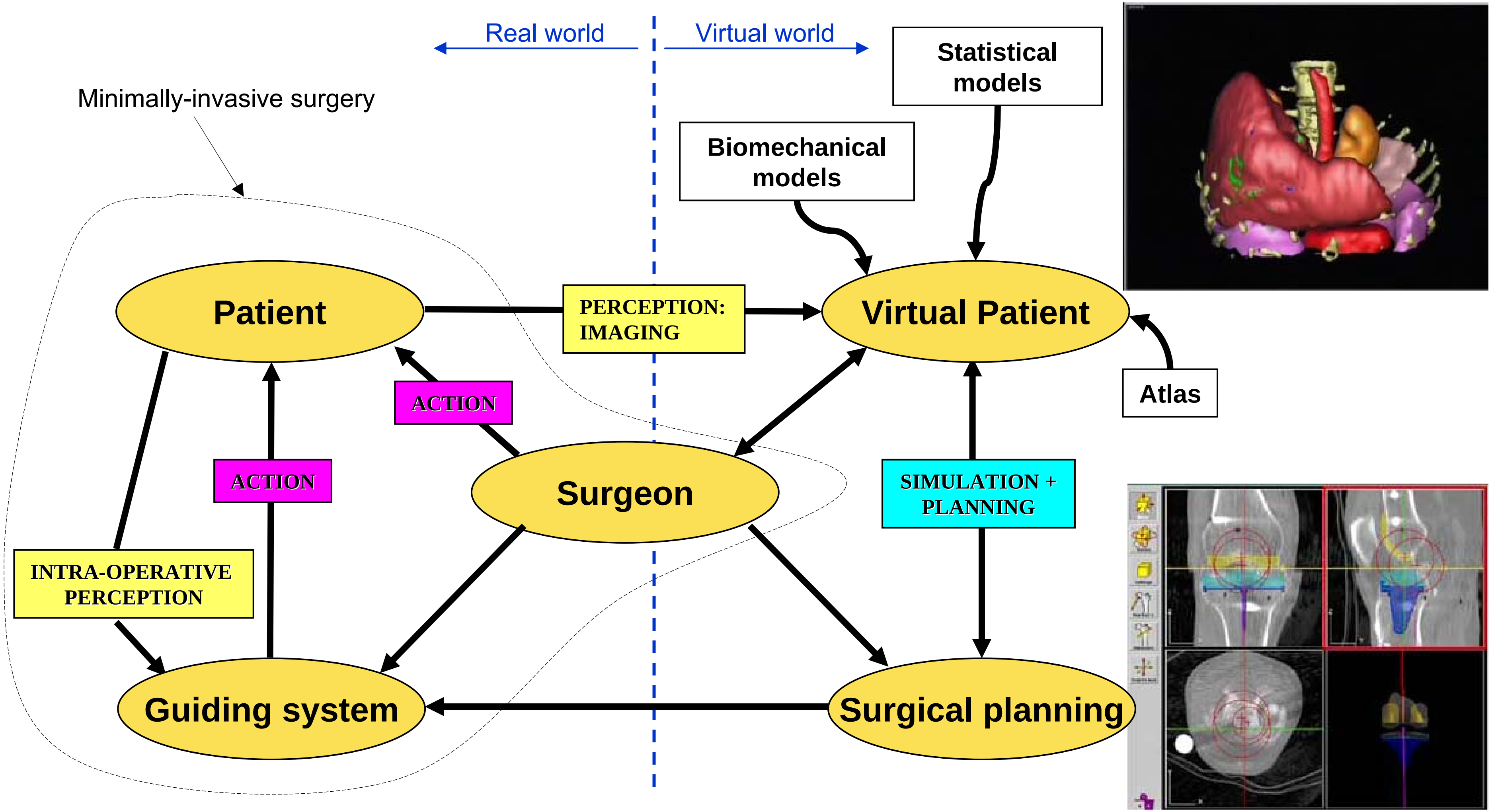


Outline

- A short overview on assistive technologies & rehabilitation robotics
- A more detailed introduction to surgical robotics
  - Analysis of some surgical functions and limitations of manual procedures: “Machining”, Constrained manipulation & targeting, Microsurgery
  - State of the art
  - How can robotics help surgery?
  - Future directions of R&D and technical challenges
  - Conclusion
- Biography

State of the art:

General structure of a Computer-Aided Surgical system: the perception-planning-action loop
(revisited from S. Lavallée, PhD thesis 1989)



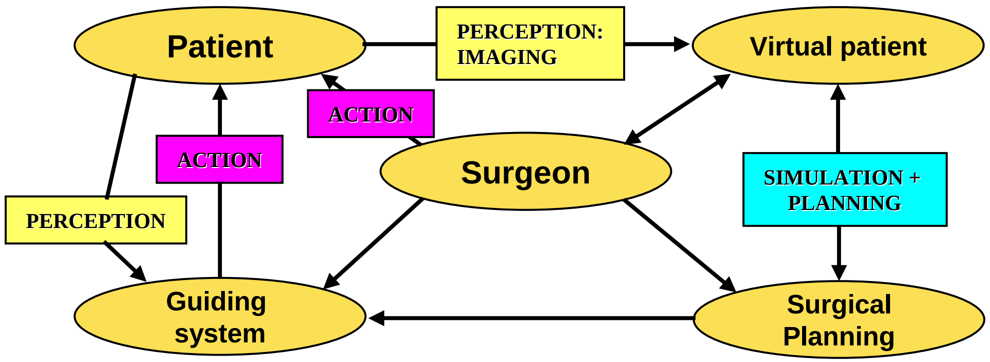
State of the art:

- Medical imaging

C. Barillot

- Design and safety

O. Company & S. Krut



- Modelling
- Simulation

O. Clatz

- Control

P. Poignet
F. Nageotte

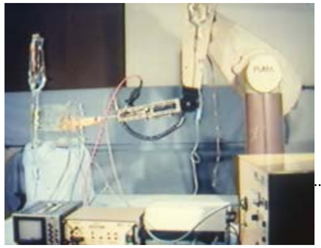
- Robot registration

J. Troccaz

- Today main robotically-assisted surgical specialities
  - Neurosurgery
  - Orthopedics
  - Minimally-invasive surgery (MIS)
  - Interventional radiology
  - Misc.: radiotherapy, maxillofacial surgery, prostatectomy, microsurgery…
- Other non surgical specialities
  - Tele-echography
  - Tele-diagnosis

Robotics for surgery and diagnosis: state of the art

- Some milestones



1985 — Neurosurgery
Puma 260
Kwoh et al.
22 patients

1989 — TransUrethral Res. of Prostate
Puma 560
(Imperial College)

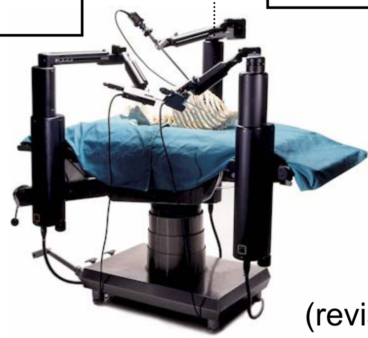
Neurosurgery
Speedy (AID robot)
Lavallée, Benhabid et al.
Hundreds of patients

1992 — Orthopedic surgery
ROBODOC (ISS), >70 robots, over 10000 patients

1994 — MIS
AESOP
(Computer Motion)
> 400

1998 — MIS Da Vinci
(Intuitive Surgical)
Still in use: > 200

MIS
Zeus
(Computer Motion)



2001 — MIS + Tele-surgery
(IRCAD)
“Operation Lindbergh”
New York-Strasbourg

Patient-mounted robot, MARS, (Mazor Tech.)

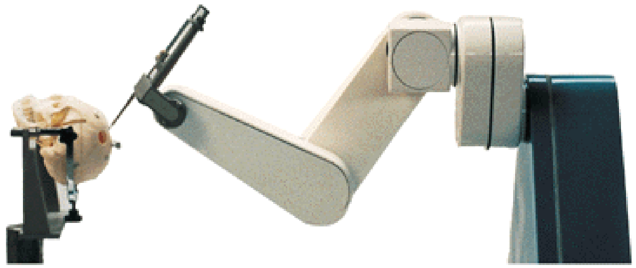
Tele-echography
SYTECH (LVR)
Bourges-Kathmandu

Transluminal endoscopic surg., (IRCAD)

(revisited from J. Troccaz, UEE 2003)

State of the art: Neurosurgery

NEUROMATE (IMMI/ISS/Schaerer-Mayfield), 1996



- Navigation systems

OrthoPilot (Aesculap)

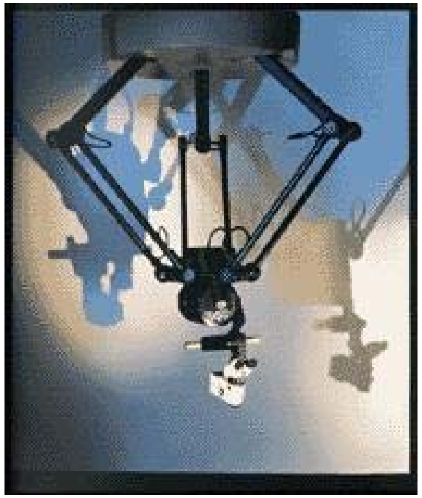
NDI

PathFinder (Prosurgics, UK)

- Robots = tool holders

The guide constrains the direction of the instrument

C. Bernard



Surgiscope (Elekta-IGS, now ISIS, France), 1997

MKM (Zeiss)

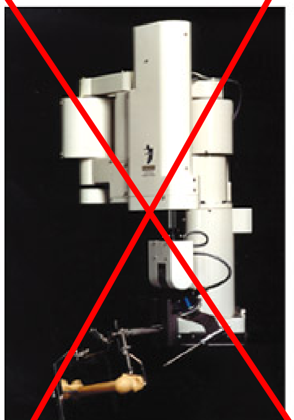
TIMC

- Microscope holders

State of the art: Orthopedics

- Navigation systems
- Robots : Industrial robots ➔ Dedicated systems ➔ "Portable" robots

E. Stindel



ROBODOC (ISS), 1992

CASPAR (OrtoMaquet / URS Ortho), 1997

ACROBOT (Imperial College/Acrobot Ltd), 2001

BRIGIT (MedTech/Zimmer, LIRMM), 2005

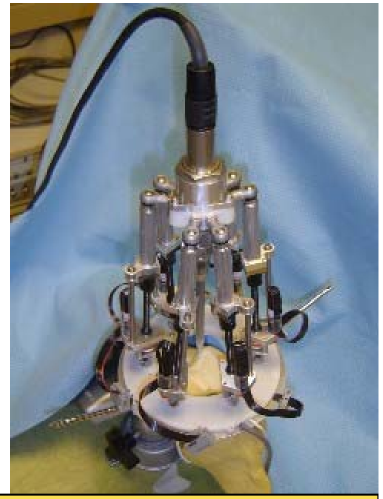
MARS (Technion/Mazor SurgIcal Haifa), 2002

State of the art: Orthopedics

- **Advantages of patient-mounted robots**
  (L. Joskowicz, CARS, Berlin 2005)
  - Small size/footprint - minimal obstruction
  - Close proximity to surgical site
  - No patient/anatomy immobilization
  - No tracking/real-time repositioning
  - Small workspace - fine positioning device
  - Potentially higher accuracy
  - Intrinsic safety due to small size/low power

6 dof

MARS (Technion/Mazor Surg. Haifa), 2002: spine surgery



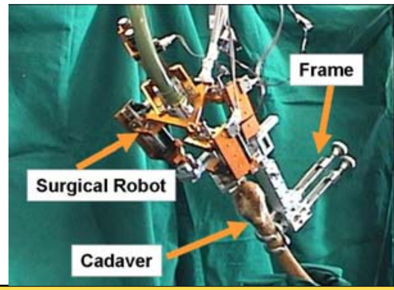
MBARS (CMU, Pittsburg): TKA

5 dof

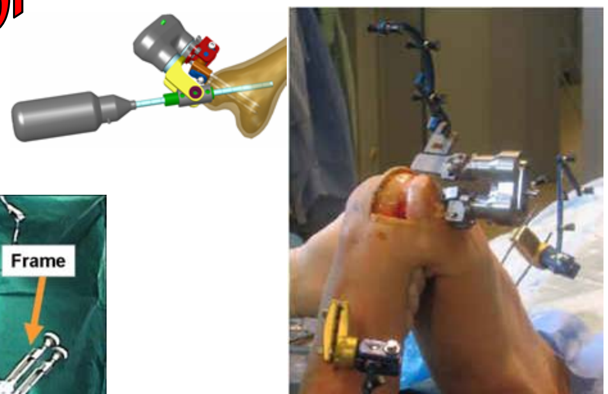
GP system (Medacta, Switzerland): TKA

PIGalileao CAS (PLUS Othopedics AG, Switzerland): TKA

2 dof



ARTHROBOT (KAIST), 2002: TKA

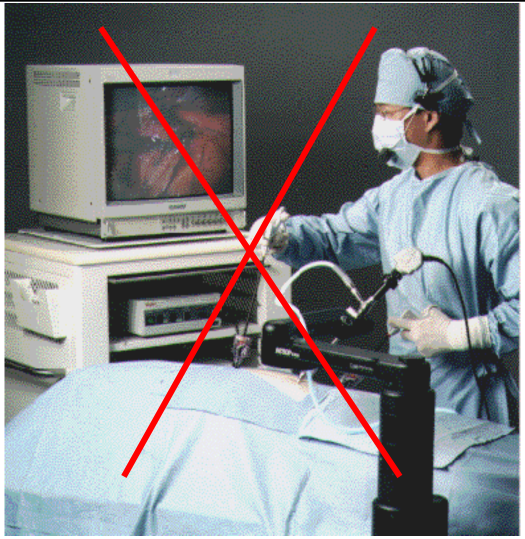


Praxiteles (TIMC): TKA

State of the art: Minimally-Invasive Surgery (MIS)

- Endoscope holders

AESOP (Computer Motion), 1992



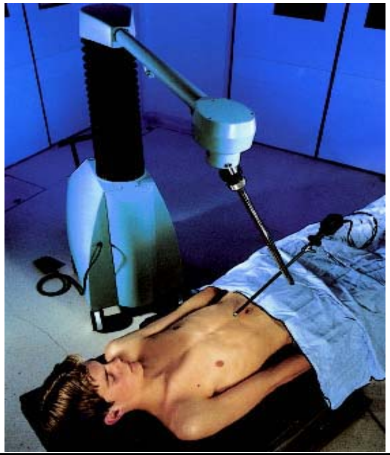
Arms with kinematic constraints to provide a remote rotation center

Voice control, Foot control

Naviot (Hitachi, Japan)

Hand control

Lapman (Medsys, Belgium)



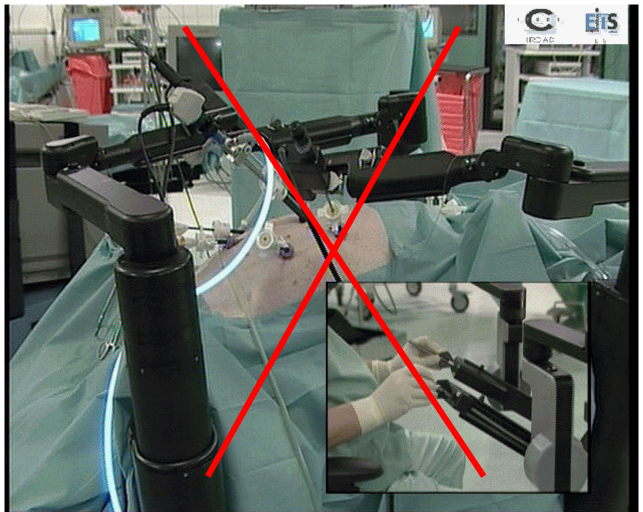
EndoAssist (Armstrong Healthcare/Prosurgics, UK)

Head control

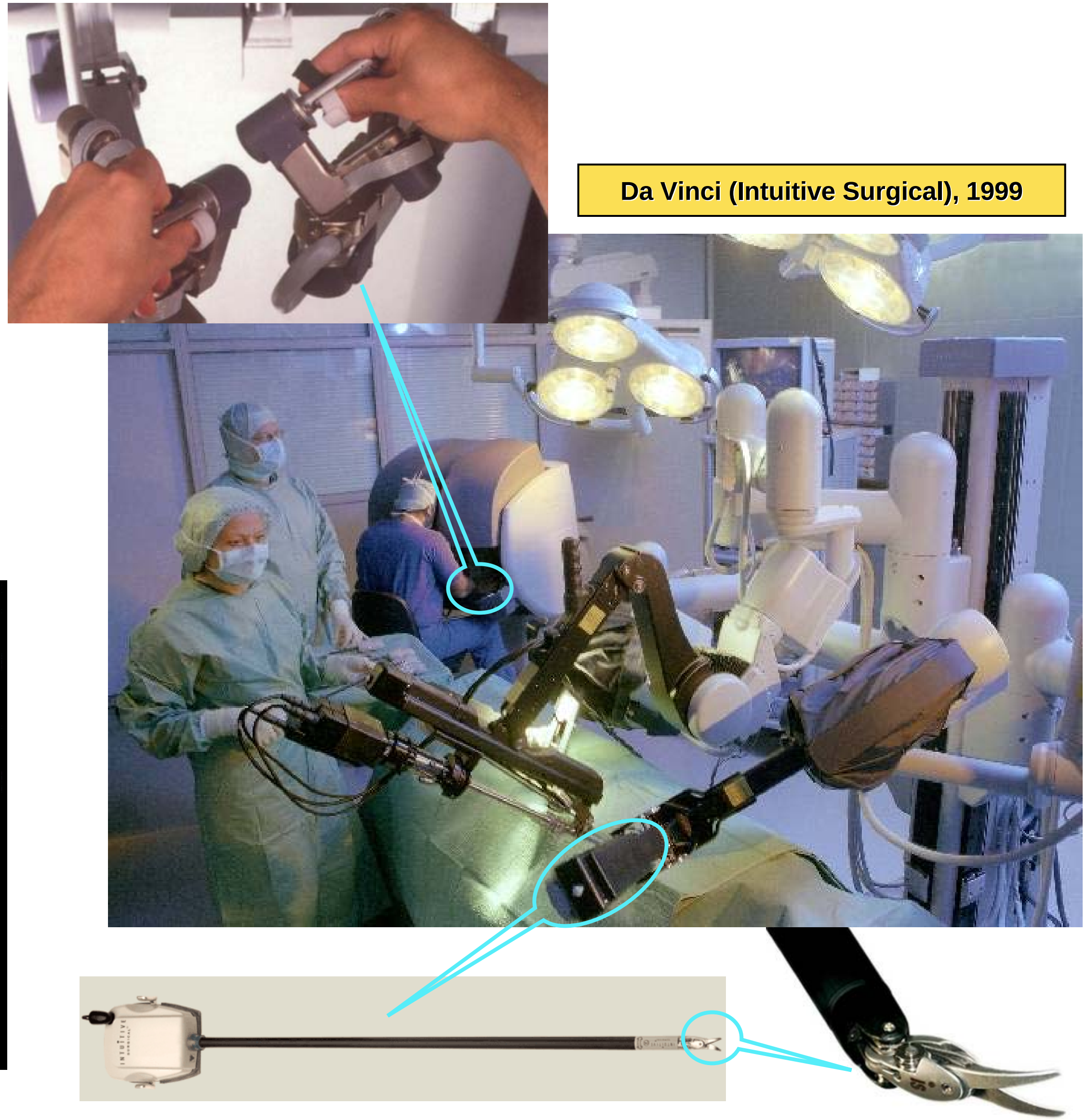
State of the art: Minimally-Invasive Surgery (MIS)

- Master-slave robots

Laprotek (Endovia Medical)



ZEUS (Computer Motion), 1998



Da Vinci (Intuitive Surgical), 1999

State of the art: Minimally-Invasive Surgery (MIS)

daVinci.avi

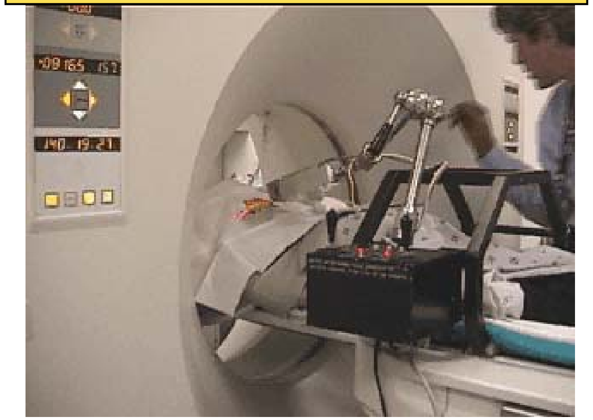
L. Soler

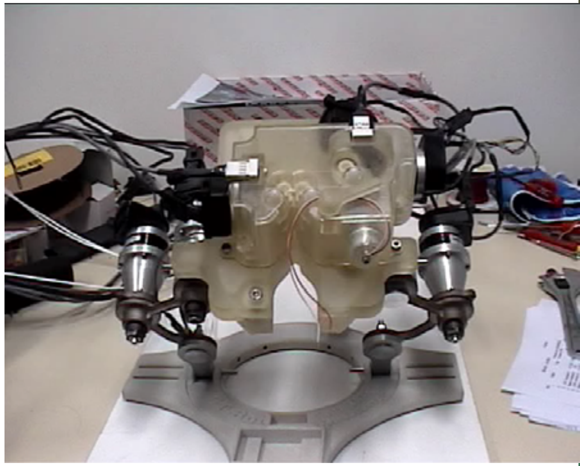
N. Bonnet

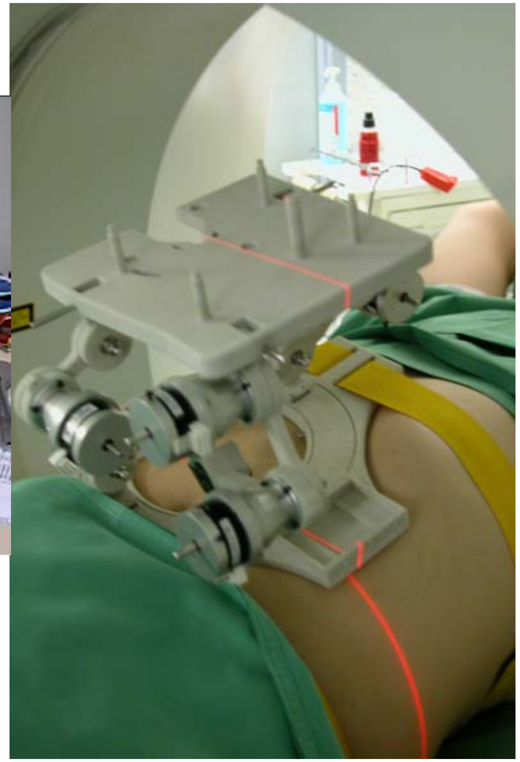
State of the art: Interventional radiology

To reach a target under image guiding...

ACUBOT (JHU, Baltimore & Georgetown Univ. Washington)







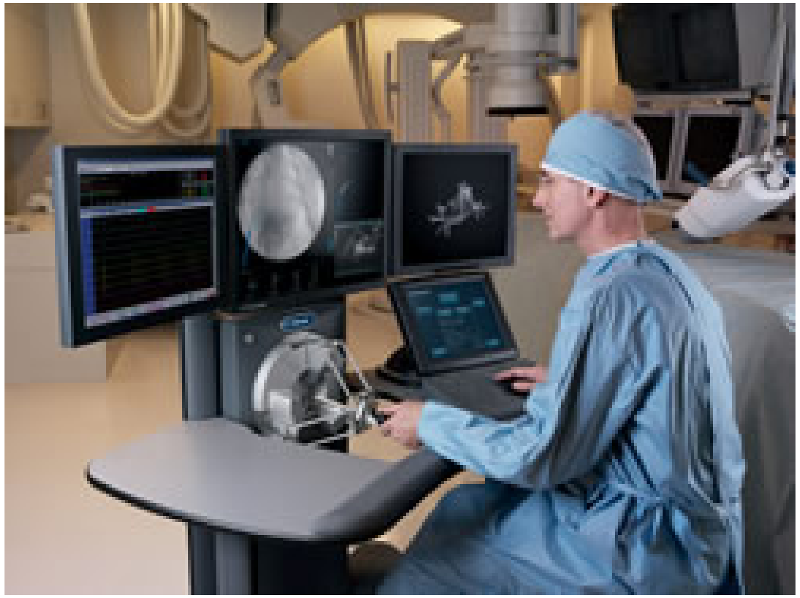
CT-BOT (LSIIT, Strasbourg), 2005

CT/MRI compatible biopsy robot (TIMC), 2004

- parallel robot
- CT-image servoing (target + compensation of physiological motions)
- 5 dof + 2 dof for needle insertion
- piezoelectric actuators
- force sensor (teleoperation mode)

State of the art: Interventional radiology

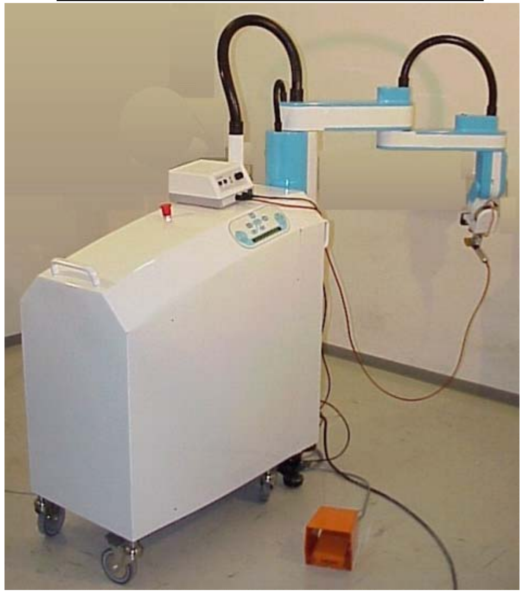
Sensei Robotic Catheter System (Hansen Medical, Mountain View, CA), 2002



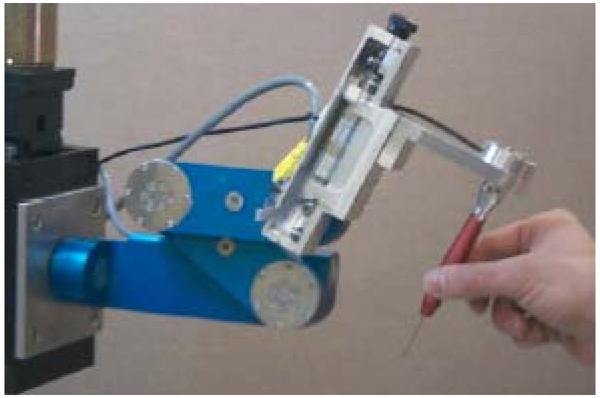
- Steerable catheter for percutaneous procedures
- Remote accurate positioning, manipulation and stable control in 3D
- « Instinctive » control: the catheter immediately replicates the hand movement of the motion controller

State of the art: Other surgical specialities

SCALPP (LIRMM/SINTERS), 2002, Skin harvesting



Bloodbot (Imperial College, London)



Steady-hand robot (JHU, Baltimore): microsurgery

And many other prototypes ...

PROBOT (Imperial College, London): prostate resection

H. Wörn W.T. Ang R. Taylor G. Morel

State of the art: Other surgical specialities

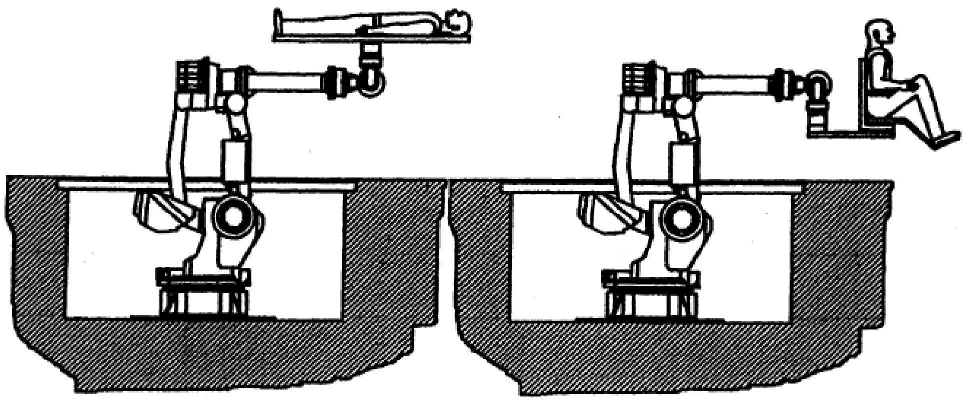
Radiotherapy: the tumor is targeted from multiple radiation ports to minimize radiations on critical areas

Cyberknife (Accuray, Stanford): radiotherapy

A lightweight linac is mounted on the robot. Tracking of respiratory motion

Centre de Protonthérapie (Orsay): radiotherapy

The patient is on a bed mounted on the robot.



Système de mise en place des patients par l'utilisation d'un robot permettant les irradiations en position assise ou couchée, avec des mouvements de précision selon 6 degrés de liberté (A. Mazal et al.)

State of the art: Tele-echography

Remote control of an echographic probe: to enable an expert in the hospital to examine a patient at home, in an emergency vehicle, in a remote clinic...

SYRTECH (LVR-Bourges), 2001

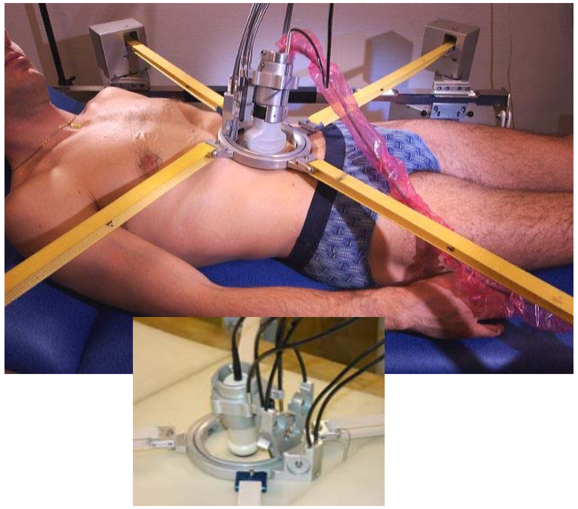
HIPPOCRATE (LIRMM/SINTERS), 1999

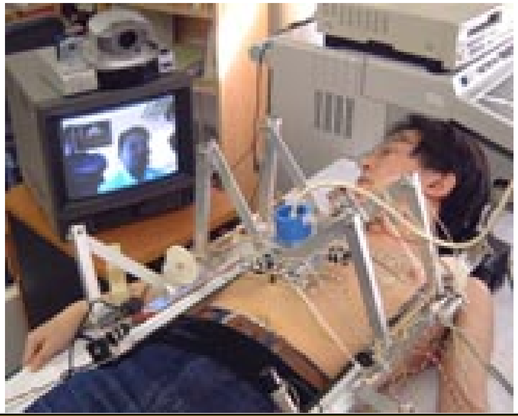
The Ultrasound robot (UBC), 1999

TERESA (LVR-Bourges/ SINTERS), 2003

ESTELE (Robosoft), 2007

TER (TIMC), 2001





Masuda Lab. Tokyo Univ. A&T, 1999

State of the art: Tele-diagnosis

Companion (InTouch Health, Goleta, CA, USA)

Healthcare through a “Remote Presence” Robot, RP-6: the doctor is projected to another location where the patient is located

- **Today commercial systems**
  - Navigation systems for neurosurgery, orthopedics & maxillofacial surgery***: *StealthStation (Medtronic), VectorVision (BrainLab), Surgetics (Praxim), Navigation System (Stryker), OrthoPilot (Aesculap), Galileo (PI Systems), InstaTrack (GEMS), Acustar (Z-Cat)…*
  - Neurosurgery / Microscope holders: *Surgiscope (ISIS), MKM (Zeiss*)*
  - Neurosurgery / Robots: *Neuromate (Schaerer-Mayfield), PathFinder (Armstrong Healthcare/Prosurgics)*
  - Orthopedics: *ROBODOC (ISS*), ACROBOT (Acrobot Ltd), MARS/Smart Assist (Mazor Surgical Technologies), BRIGIT (MedTech/Zimmer)*
  - MIS: *Da Vinci (Intuitive Surgical), ZEUS (Computer Motion**), EndoVia Medical**
  - Endoscope holders: *AESOP (Computer Motion**), EndoAssist (Armstrong Healthcare/Prosurgics), Lapman (Medsys), Naviot (Hitachi)*
  - Interventional radiology: *Sensei (Hansen Medical), CorPath (Corindus)*
  - Radiotherapy: *Cyberknife (Accuray)*

  - Tele-echography: *Estele (LVR / Robosoft)*
  - Tele-diagnosis: *Companion (InTouch Health)*

* out of business
** merged with Intuitive Surgical since March 2003
*** lecture of Y. Patoux, “Evolution of surgical navigation during past decade", http://www.lirmm.fr/UEE05/

State-of-the-art: commercial systems

Industrial forum
(Friday afternoon)

Company	Location	Activity	Web site
EndoControl	Grenoble, France	Robotics for endoscopic surgery (VIKY / LER)	http://www.endocontrol-medical.com/
Force Dimension	Lausanne, Switzerland	Haptic devices	http://www.forcedimension.com/fd/avs/home/
Haption	Soulge sur Houette, France	Haptic devices	http://www.haption.com/
Impella Cardiosystems Abiomed	Aachen, Germany	Heart recovery and assist device	http://www.abiomed.com/europe/index.cfm
Koelis	La Tronche, France	CAS systems for to diagnosis and therapy in urology	http://www.koelis.com/
Robosoft	Bidart, France	Tele-echography (ESTELE healthcare robot)	http://www.robosoft.fr/eng/
Given Imaging SAS	France	Capsule endoscopy (PillCam)	http://www.givenimaging.com/Cultures/en-US/given/english

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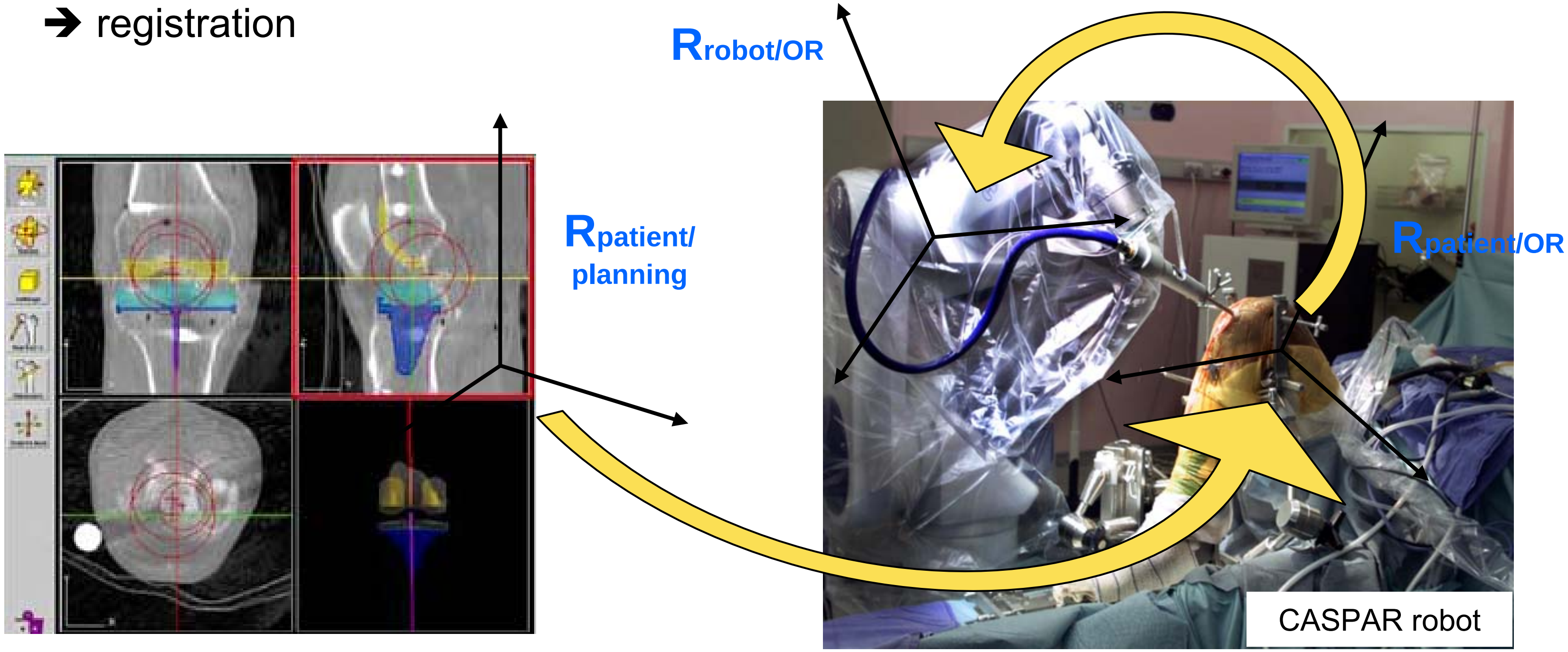
- **Several difficulties of manual surgical procedures that a robotic system can help to solve:**
  - Precise localization (position and orientation) of instruments wrt to patient with reference to pre-operative planning or intra-operative imaging:

    ➔ registration



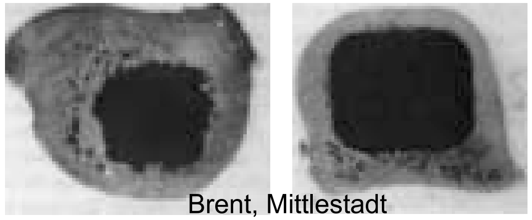
(ORTHODOC. Source R. Taylor, 1st Summer School in Medical Robotics 2003)

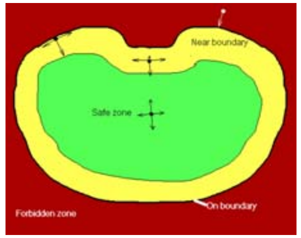
Pre-operative data

Intra-operative data

How can robotics help surgery?

- **Several difficulties that a robotic system can help to solve:**
  - Precise localization (position and orientation) of instruments with reference to pre-operative or intra-operative imaging
  - Complex and accurate path following (e.g. milling a cavity in a bone, targeting a tumor from multiple radiation ports…)
  - Cancel the hand-eye coordination problem (e.g. in MIS)
  - Real time integration of intra-operative data:
    - image-guided motion (e.g. needle insertion)
    - visual-servoing (e.g. to compensate for physiological motions and patient's motions)
    - force-controlled motion (e.g. machining, skin harvesting), …
  - Limitation of risks: possible to constrain the instrument to move into safe regions
  - Heavy loads (e.g. linac, microscope…)
  - 3rd hand…


Brent, Mittlestadt



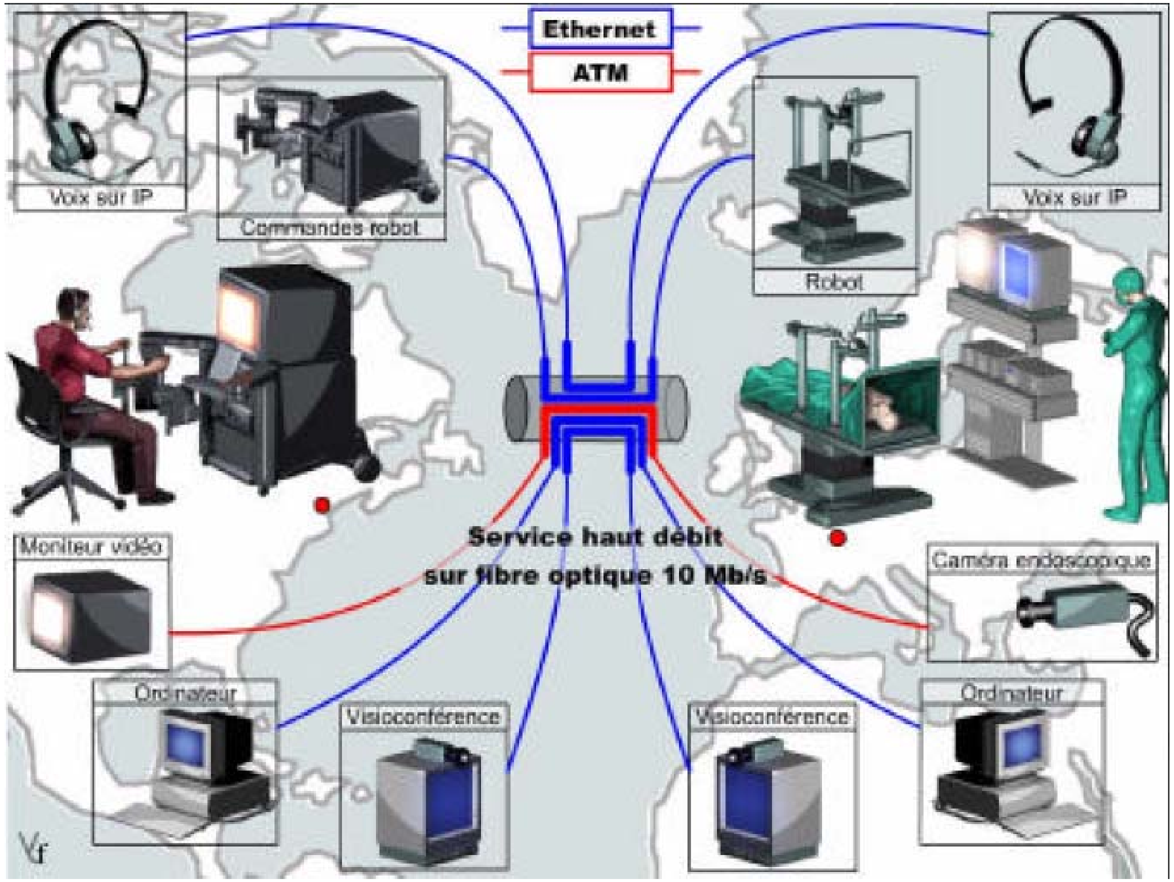
Acrobot

- **… and improvements that can be expected wrt manual procedures:**
  - Compensation for surgeon's hand tremor
  - Motion and force augmentation or scaling (e.g. for microsurgery)
  - Better comfort for the surgeon…

- **Some expected "added-values" of robots…**
  - *In neurosurgery, percutaneous therapy, radiosurgery:*
    - limits collateral effects due to lesions of instruments or radiations
    - accessing smaller and smaller targets closer and closer to vital areas
    - removes the operator from hazardous environment such as X-ray
  - *In orthopedic:*
    - less revision surgeries
    - longer life expectancy of protheses
    - less risk (e.g. pedicular screw placement)
    - reduction of the number of instruments required during surgery
  - *In MIS:*
    - control of additional mobilities at the distal part of instrument
    - haptic feedback
    - performing surgeries that cannot be executed manually (e.g. beating heart surgery)
    - compensation for physiological motion
  - *Long distance surgery*

State of the art: assessment

Lindbergh operation (IRCAD Strasbourg, France Télécom,Computer Motion)
September 7th, 2001, New York – Strasbourg (15 000 km), Human cholecystectomy



Demo Teleop. Montpellier-Seattle B. Hannaford

Latency or delay cannot exceed 200 ms

Reprinted from
L. Soler, IRCAD

State of the art: assessment

- **Some expected "added-values" of robot: less invasive, more accurate, improvement of surgeon's capabilities…**
- **… but also some reserve to the use of a robotic system in the OR:**
  - Cost effectiveness **not yet proved** (source B. Armstrong, CARS Berlin, 2005):
    - increase OR cost
    - technical team in the OR
    - training of the surgical team
    - setup and skin-to-skin times longer than conventional procedure
  - Clinical added value **not yet clear:** *"it is difficult to prove their effectiveness since there are no established methods to relate conventional (non robotic) techniques that would serve as benchmarks* …"
  - Compatibility with the environment of the OR (cluttered, other electrical devices…): **yet too bulky**
  - **Safety**
    - the robot shares its working space with surgical staff and patient
    - "trail & error" or "doing again" motions are not allowed
    - sterilizability constraints

➔ **Still a lot of technical and clinical (new procedures) research work**

See also http://www.nsf.gov/eng/roboticsorg/IARPMedicalRoboticsWorkshopReport.htm

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C. Stefanini

Future directions of R&D and technical challenges

- **Technical challenges**
  - lightweight, smaller, simpler, cheaper,
  - integration in the OR: plug-and-play systems
  - sensors: sterilizable or disposable
  - MMI: real cooperation between Surgeon and Robot (“Hands-on” / Comanipulation concept: the surgeon operates the device)…

- **Trends:**
  - Dedicated robotized / “smart” instruments
  - Autonomy

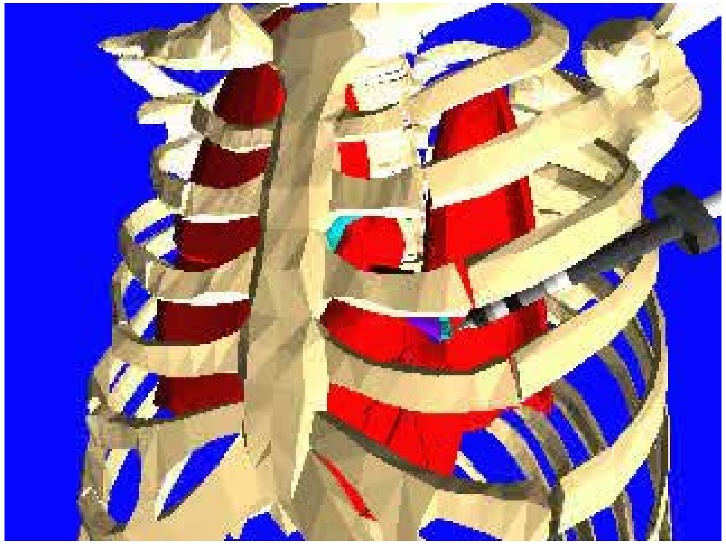
Future directions of R&D and technical challenges

- **Some examples of solutions currently explored:**
  - “Smart” instruments
  - Intra-body robots
  - Minimally-invasive beating heart surgery

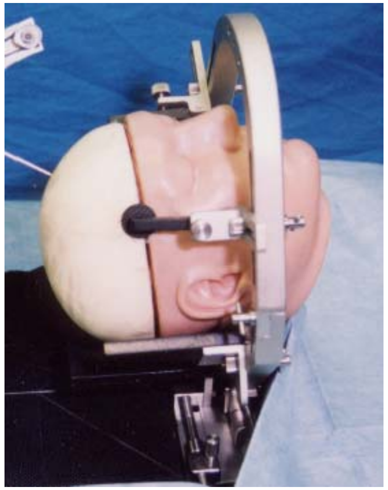
Future directions of R&D and technical challenges

- **Some examples of solutions currently explored:**
  - "Smart" instruments
    - Mini-manipulators "inside the body"
    - Active catheters
    - Robotized instruments

- **Mini-manipulators "inside the body"**
  - for instance fixed on the trocar
  - high dexterity: must provide bending + eventually extension and obstacle avoidance capabilities
  - size requirements : Ø < 10mm, L = a few cm, small radius of curvature
  - force: a few Newtons (penetration force in a coronary artery = 1N), up to 50 N to grasp a needle
  - main technical issues: miniaturization; force sensor; sterilizability…



Cardiac surgery (D. Sallé, LRP)



Neurosurgery

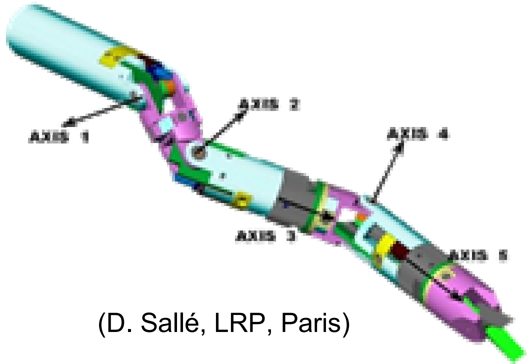
Future directions of R&D and technical challenges: Smart instruments (2/9)

- **Mini-manipulators "inside the body"**

➔ Two approaches

- discrete ("classical") mini-serial manipulator made of rigid bodies and joints) with embedded actuators+ gear transmissions:

  bulky, power limitation, low reliability



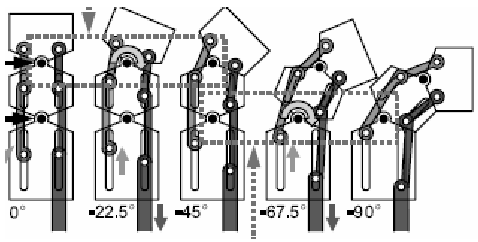
(D. Sallé, LRP, Paris)

- or continuous backbone ("snake-like") architecture made of flexible material (cable, elastomer, bellows…) and remotely actuated

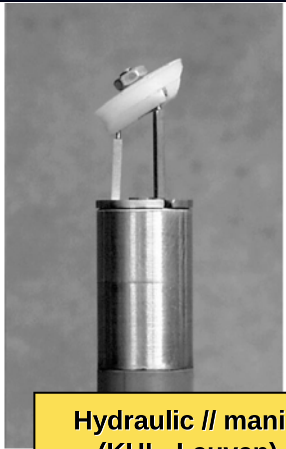
  high dexterity

(Univ. Tokyo)

- limitations of remote actuation:
  - mechanical linkages: bulky
  - cable-drives: backlash, limited reliability
  - SMA wires (NiTi): large stroke length / weight ratio but limited bandwidth



Future directions of R&D and technical challenges: Smart instruments (4/9)

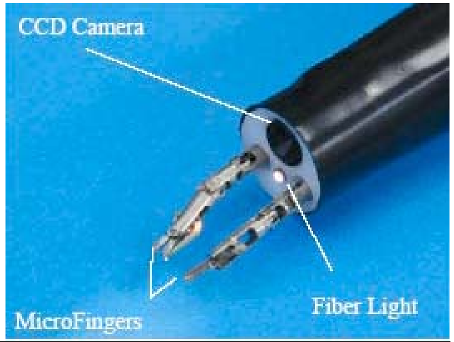


Hydraulic // manipulator (KUL, Leuven), 2000

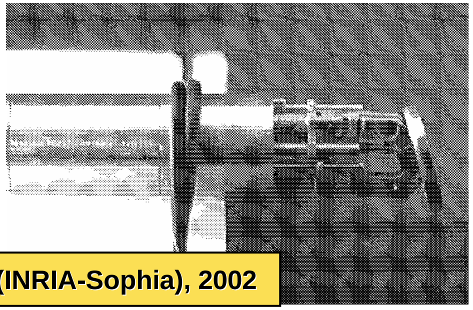
HARP (Robotics Institute, CMU, Pittsburg), 2006

Bending forceps (Hitachi, Japan), 2000

Bending forceps based on rigid linkage mechanism (Univ. Tokyo), 2003

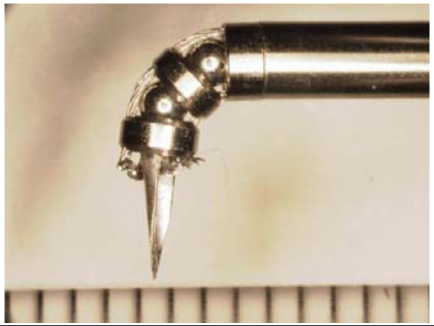


Endoscopy surgery system (Nagoya Univ.), 2004

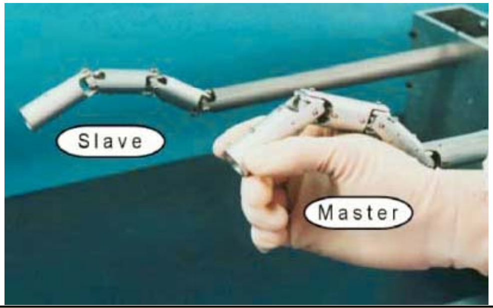


MIPS (INRIA-Sophia), 2002

Bending US coagulator/cutter (Women's Medical Univ. Tokyo), 2004



Micro-manipulator for Intrauterine fetal surgery (Wasesa Univ., Japan), 2005

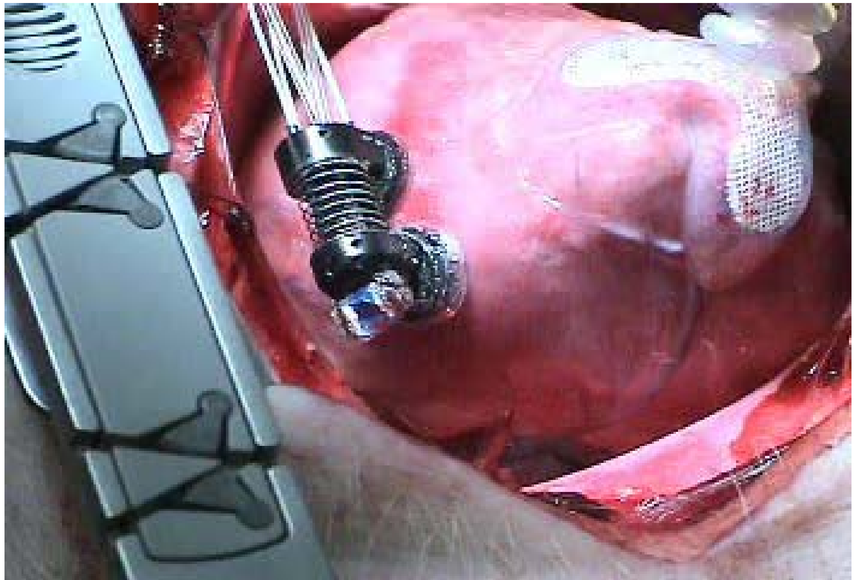


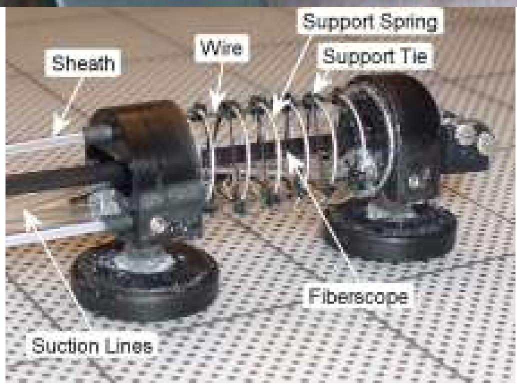
HyperFinger (Nagoya Univ., Japan), 2003

Future directions of R&D and technical challenges: Intra-body robots (5/9)

HeartLander (The Robotics Institute, CMU, Pittsburgh)

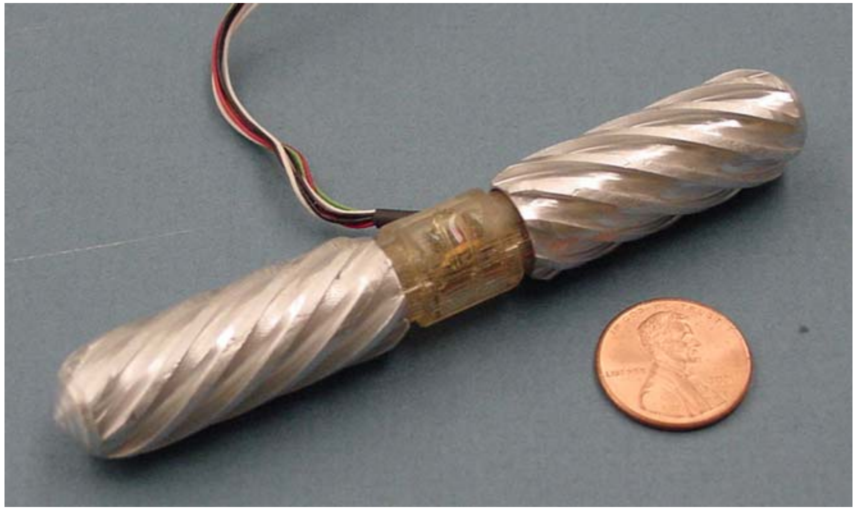
… an inchworm-like mobile robot for minimally-invasive beating-heart cardiac surgery

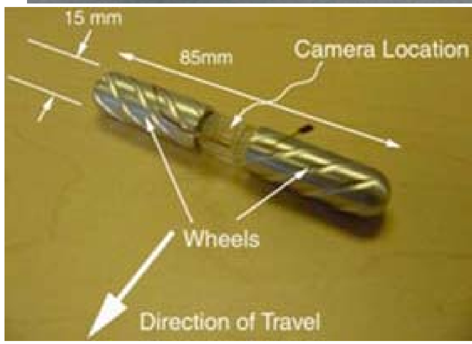


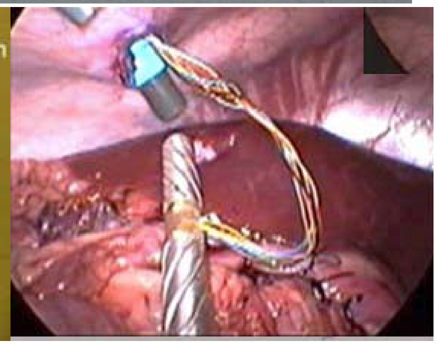


(Robotics & Mechatronics Lab., Univ. Nebraska)

… a wheeled-driven mobile robot to be placed in the abdominal cavity



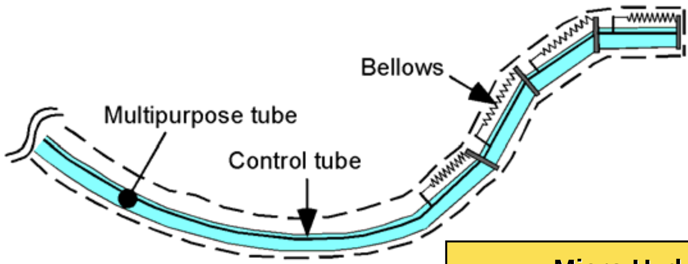




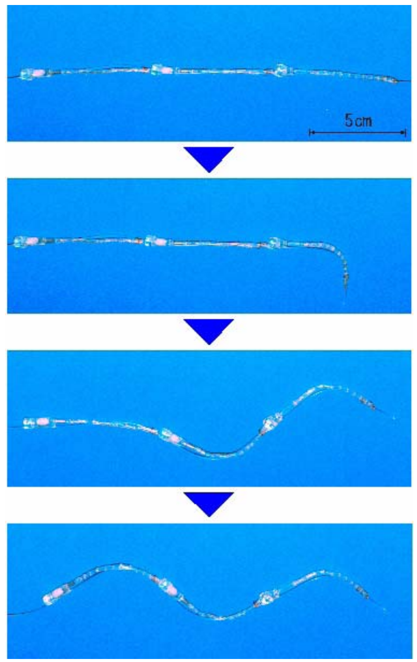
Future directions of R&D and technical challenges
Smart instruments (6/9)

- **Active catheters**
  - Catheter: a tube that can be inserted into a body cavity duct or vessel. Catheters thereby allow drainage or injection of fluids or access by surgical instruments (Wikipedia). Also used for angioplasty, blood pressure measurement...
  - Typical sizes: Ø <2-3 mm, L > 1m
  - Manually introduced by the surgeon, often at the level of the groin in the femoral artery, by pushing and rotating actions under X-ray control
  - Difficulty: transmit force and motion to the catheter tip with no or poor tactile feedback while minimizing X-ray irradiation. Risks of perforation of the artery or vein

➔ Solution
  - Active bending of the tip
  - Actuation: Hydraulic, SMA, ICPF…



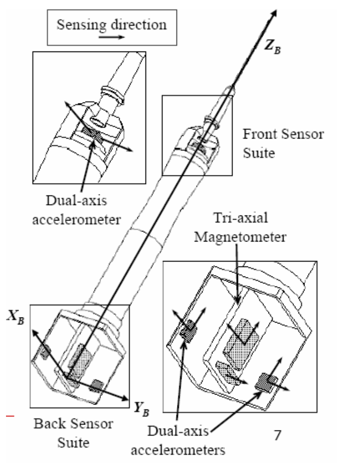
Ø = 1.5 mm, L = 15 cm

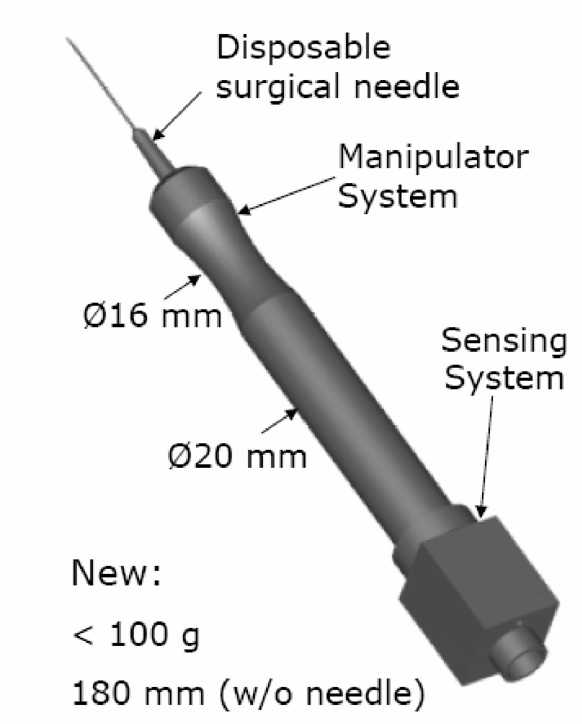


Micro Hydraulic Active Catheter with micro-valves (Nagoya Univ., Japan)

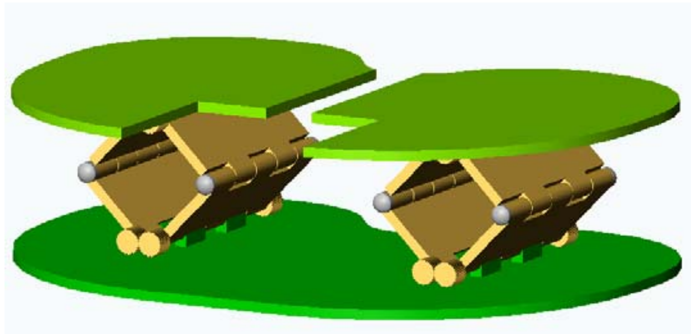
- **Robotized instruments**

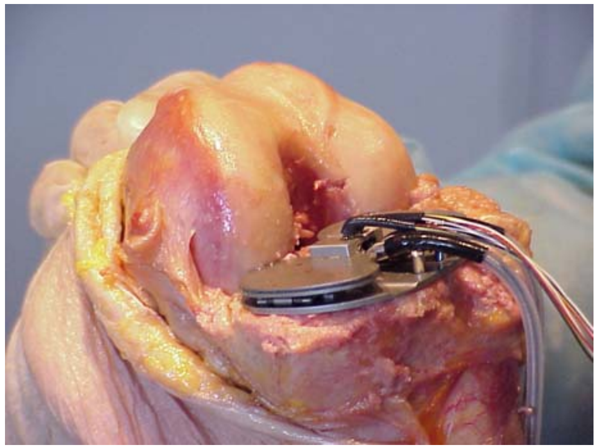
MICRON tremor cancelling instrument (CMU, Pittsburgh): eye surgery





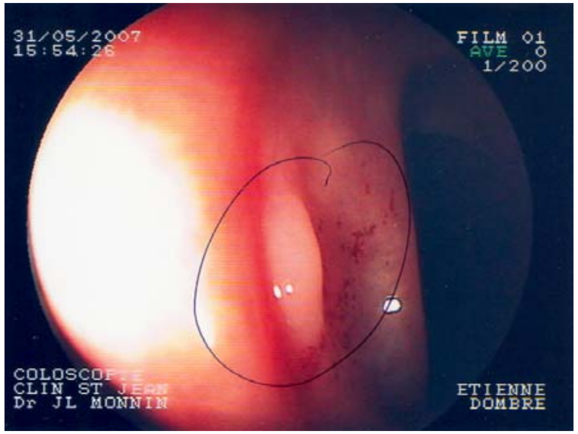
Robotized spacer for ligament balance in TKA (TIMC, Grenoble)



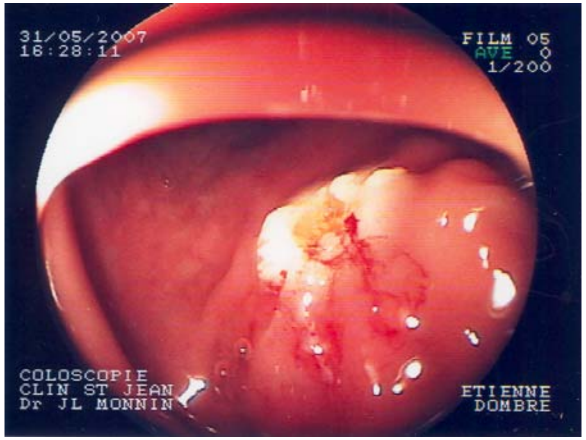


- **Some examples of solutions currently explored:**
  - “Smart” instruments
  - Intra-body robots
  - Minimally-invasive beating heart surgery

- **Intra-body robots**
  - Goal: Inspection of the gastrointestinal tract (small intestine, colon).
  - Colon cancer: one of the main causes of death in the industrialized countries
  - Currently, manual colonoscopy: push-type flexible endoscope (up to Ø 2cm) with CCD camera, optical fiber for illumination, working channel (air, water, wire-actuated instruments for biopsy…)
  - Detection and resection of polypus

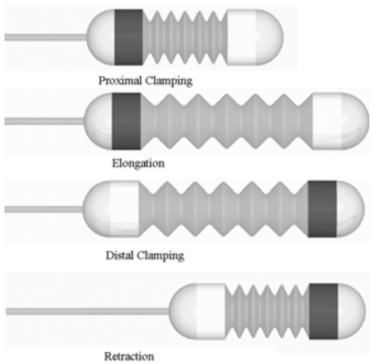


  - Difficult, painful and hazardous procedure



Future directions of R&D and technical challenges
Intra-body robots (1/5)

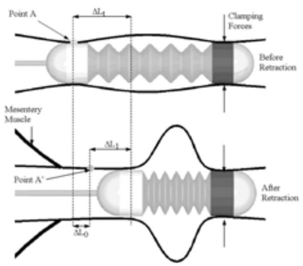
- Solutions
  - Semi-autonomous colonoscope: self propelling robot with a tether to transport fluids and energy
  - Autonomous untethered pill swallowed by the patient (thus, the whole tract may be inspected)



EMIL (SSSA, ARTS Lab., Pise)

Ø = 12 mm
Lmin = 115
Lmax = 195

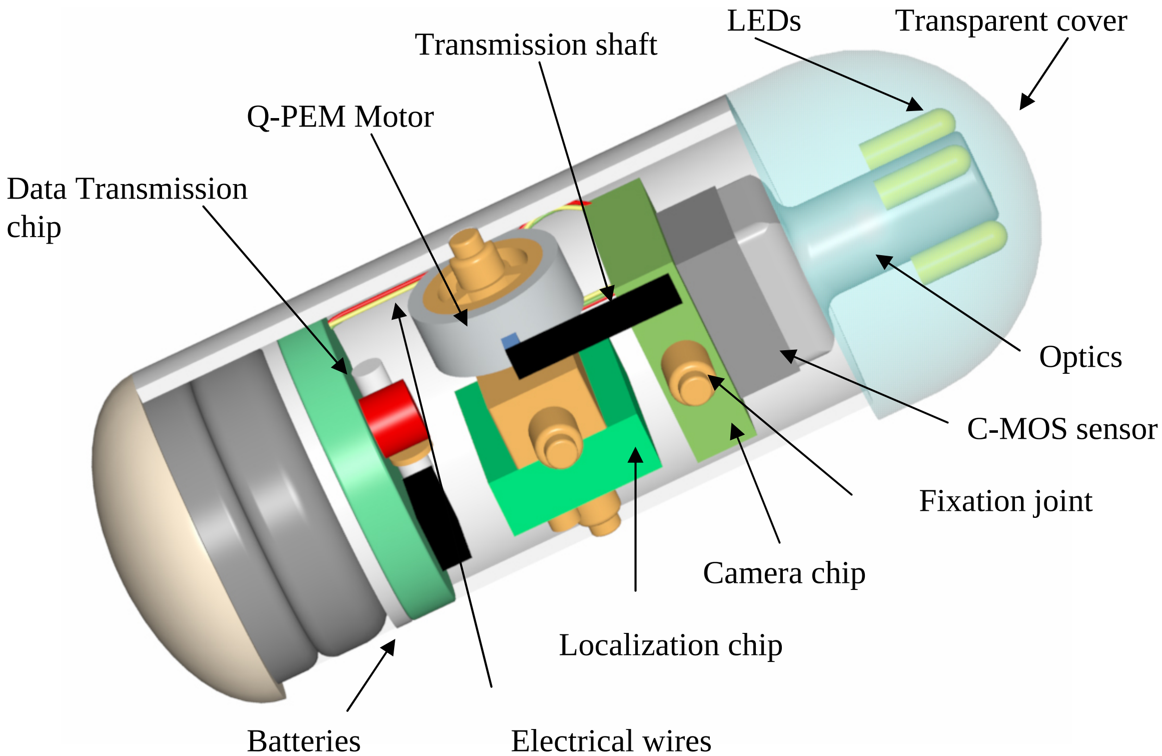
… but colon is collapsible, slippery, has acute bends, which limit traveling capabilities of semi-automatic colonoscopes

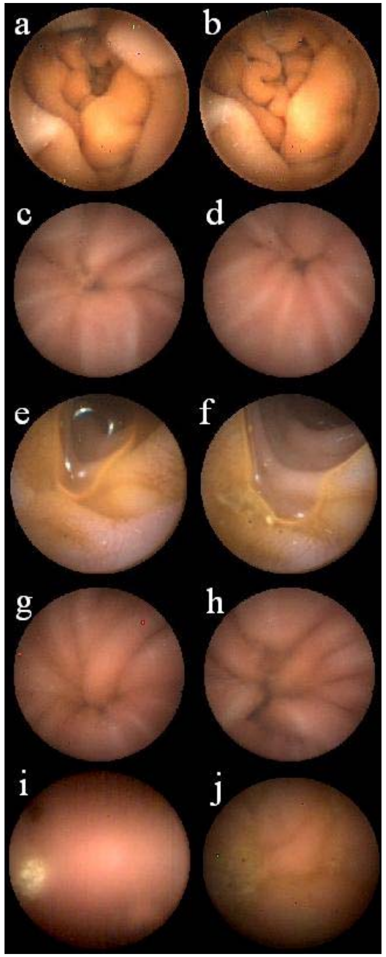


Accordeon effect

Future directions of R&D and technical challenges: Intra-body robots (2/5)

The Endoscopy « Pill »
Given Imaging – M2A



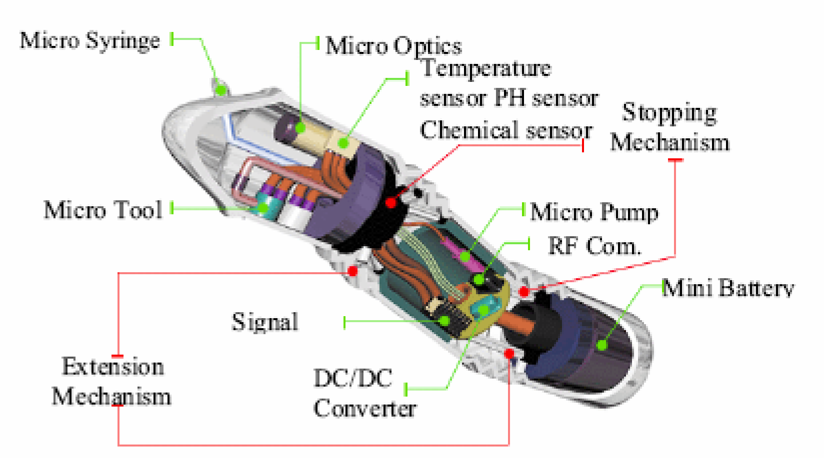


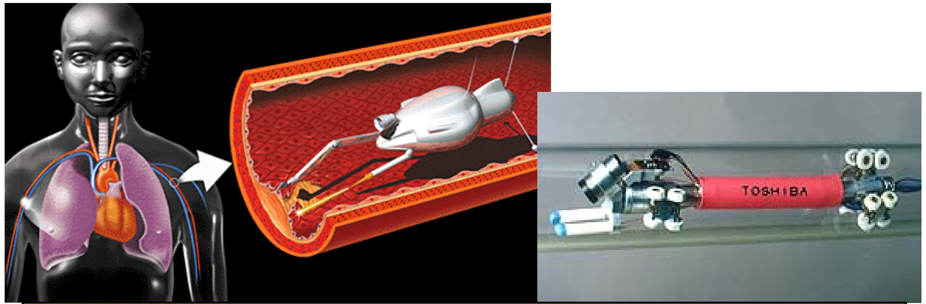
Intracorporeal Video Probe

L = 20 mm, Ø = 8 mm
CMOS technology
RF trasmission data
With steerable camera

Future directions of R&D and technical challenges: Intra-body robots (3/5)

Microcapsule for gastrointestinal diagnosis and therapy (IMC, Korea)





"In pipe" inspection microrobot (weight: 16g) (Toshiba, Japan)

Sayaka, Japan, 2005

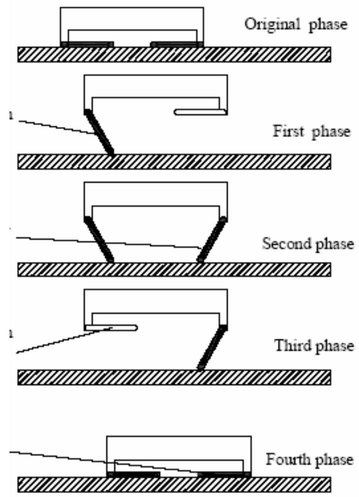
The Endoscopy « Pill » M2A (Given Imaging, Israel), 2001

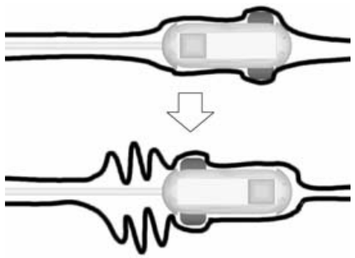
Norika3 et (RFSystem Lab., Japan), 2001

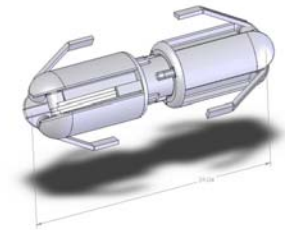
Smart capsule endoscope (Olympus Co., Japan)

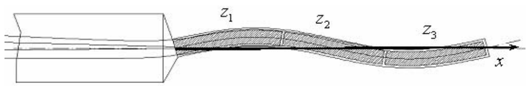
Future directions of R&D and technical challenges
Intra-body robots (4/5)

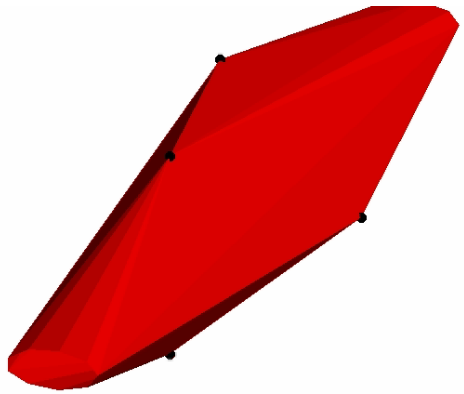
- Technical issues
  - Miniaturization, energy
  - localization of the pill in the tract
  - Active locomotion (wrt natural peristaltic waves of the tract):
    - biomimetic approaches: Inchworm, legs (SSSA), cilia, swimming (fins, tails)
    - sliding clampers
    - paddling
    - inertia impact





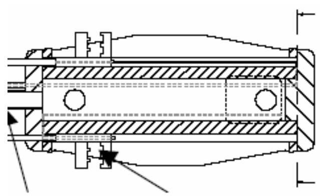


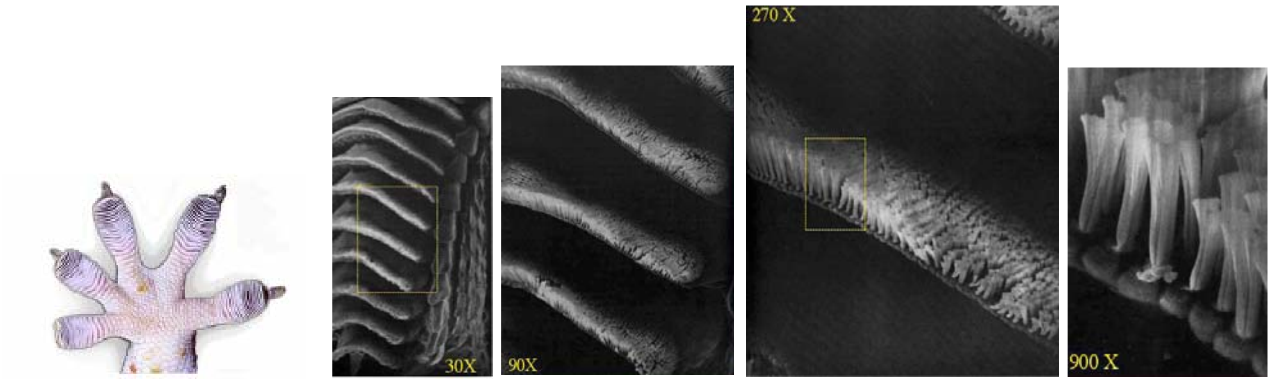




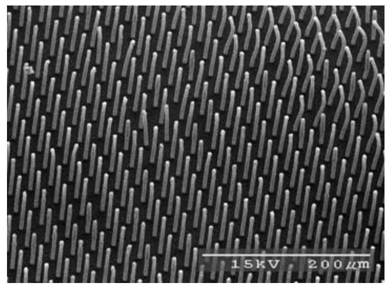
Future directions of R&D and technical challenges
Intra-body robots (5/5)

- Technical issues
  - Miniaturization, energy
  - localization of the pill in the tract
  - Active locomotion (wrt natural peristaltic waves of the tract):
    - biomimetic approaches: Inchworm, legs (SSSA), cilia, swimming (fins, tails)
    - sliding clampers
    - paddling
    - inertia impact
  - Clamping
    - biomimetic approaches: gecko, beetle, fly, cockroach pads…
    - mechanical grippers
    - suction





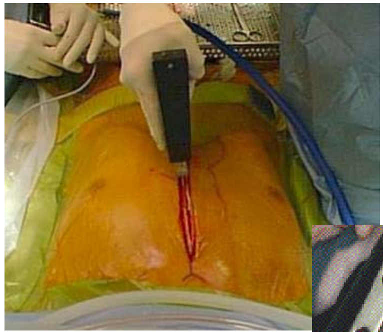
Lamellae → Setae (mm) → Nano-fibers (200 nm)

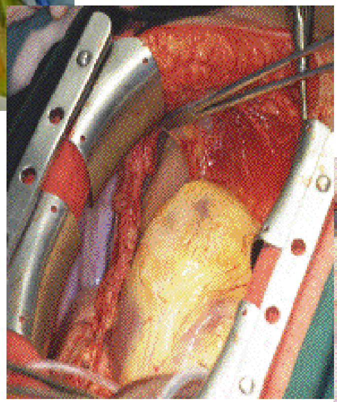


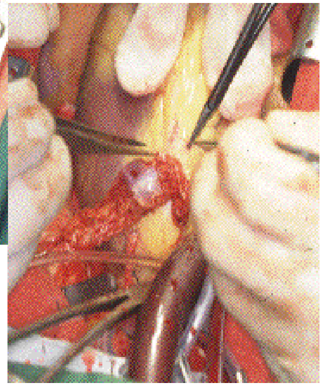
4 µm molded polyurethane fibers

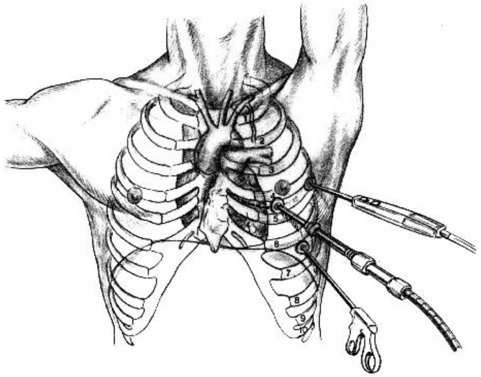
- **Some examples of solutions currently explored:**
  - “Smart” instruments
  - Intra-body robots
  - Minimally-invasive beating heart surgery

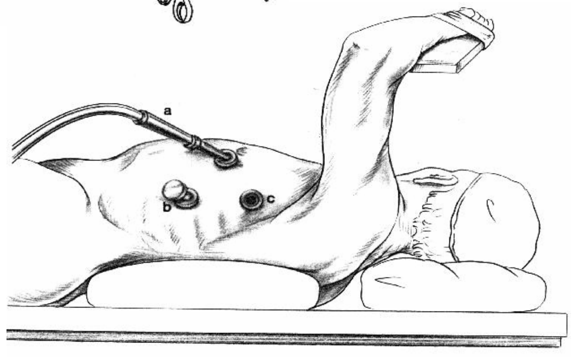
Future directions of R&D and technical challenges: Minimally-invasive beating heart surgery (2/13)











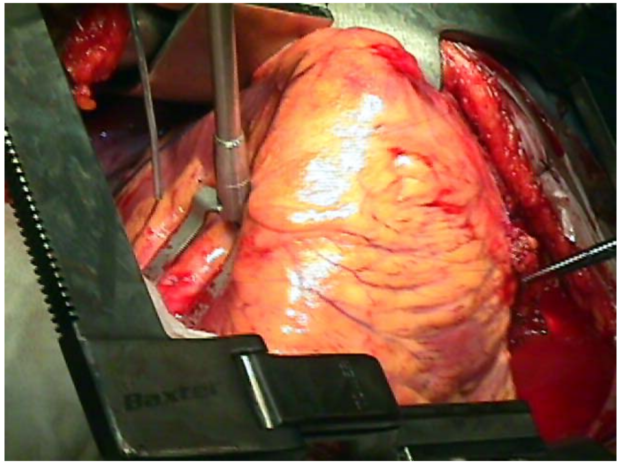
- **Invasive surgery:**
  - open the chest (sternotomy)
  - setup the heart-lung machine
  - stop the heart
  - execute the surgical gestures,
  - restart the heart and close the chest
  - many drawbacks: risk, pain…

- **Minimally invasive surgery:**
  - execute the surgical gestures through trocars without stopping the heart

- **Requirements:** compensate for physiological motions (heart beats and respiratory motions)

➔ **Solution:**
  - use of mechanical stabilizers
  - or virtually stabilize the region of interest with a robot

➔ develop appropriate vision-based (endoscopy or echography), force-based and model-based control algorithms



Octopus , Medtronic

Outline

- A short overview on assistive technologies & rehabilitation robotics
- A more detailed introduction to surgical robotics
  - Analysis of some surgical functions and limitations of manual procedures: “Machining”, Constrained manipulation & targeting, Microsurgery
  - State of the art
  - How can robotics help surgery?
  - Future directions of R&D and technical challenges
  - Conclusion
- Biography

- **… and tomorrow?**
  - *Medical robotics suffers from a "chicken and egg" phenomenon in the sense that systems need to be developed before they can be tested clinically, but only through the latter will their true effectiveness and utility be proven […]*
  - *To date, much of medical robotics research has been performed on a "technology push" rather than a "market demand" basis […]*
  - *Strategic investment in research and development is needed: we estimate several $US billion are required over the next decade. Because medical robotics has yet to show its ultimate value, it is unlikely that industry will provide much of the needed funding, hence government will have to be the main source […]*

In http://www.nsf.gov/eng/roboticsorg/IARPMedicalRoboticsWorkshopReport.htm

Conclusion

- **… and tomorrow?**

20th century

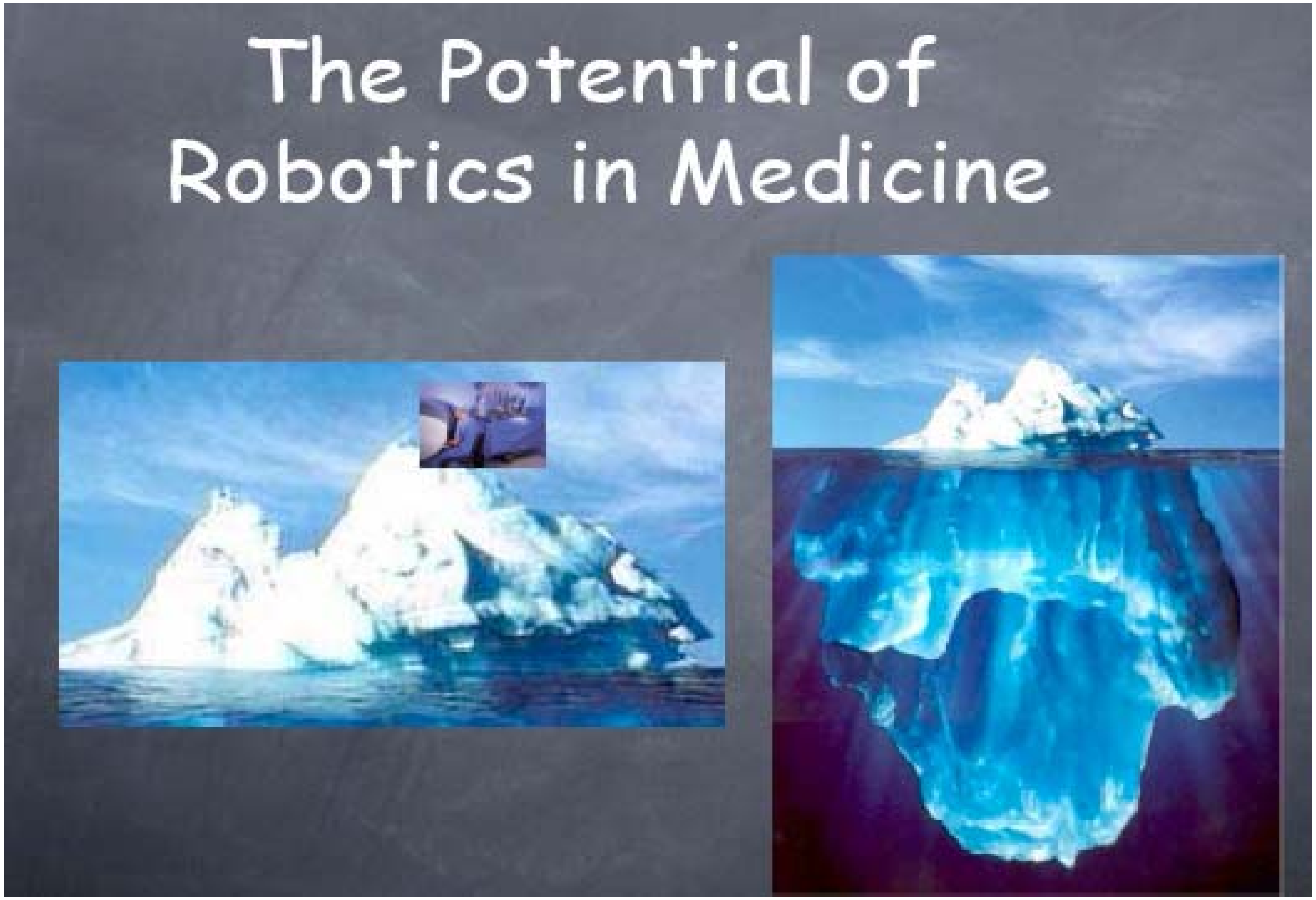
21st

DARPA Project for Military Surgery

Film Darpa

Revisited from Jacob Rosen, Univ. Washington, Seattle

Conclusion



(Source: Vance Watson, ISIS, Georgetown Univ. Hosp., Washington (CARS 2005)

Outline

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- **Suggested readings and websites:**
  - IEEE Trans. on Robotics & Automation, Special issue on Medical Robotics, Vol. 19(5), October 2003
  - IARP Workshop on Medical Robotics, Hidden Valley,May 2004: http://www.nsf.gov/eng/roboticsorg/IARPMedicalRoboticsWorkshopReport.htm
  - CARS Workshop on medical Robotics, Berlin, June 2005: http://www.caimr.georgetown.edu/Medical%20Robotics%20Workshop/main.htm
  - **1st Summer School in Medical Robotics, September 2003, Montpellier:** http://www.lirmm.fr/manifs/UEE/accueil.htm
  - **2nd Summer School in Medical Robotics, September 2005, Montpellier:** http://www.lirmm.fr/UEE2005/
  - EURON Research Roadmap (April 2004): http://www.cas.kth.se/euron/euron-deliverables/ka1-3-Roadmap.pdf
  - MICCAI, Tutorials “From mini-invasive surgery to endocavitary / endoluminal interventions”, St Malo 2004: http://miccai.irisa.fr/index2.php?menu=Exhibits_and_Workshops&page=Tutorials
  - Journals: general Robotics and Biomedical J. (IEEE RO, BME, Mechatronics,…) and more “Image processing” oriented (MedIA, JCAS, IEEE PAMI…)
  - Conferences: general Robotics conf. (ICRA, IROS, ISER…) and more dedicated: MICCAI, CARS, CA0S…