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100 years of living science

100

Body Sensor Networks –
Research Challenges and Applications

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Institute of Biomedical Engineering
Imperial College London
http://www.bsn-web.org

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Acknowledgement

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Ara Darzi

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Imperial College London: basic stats

- 2700 academic and research staff: 6 campuses
- 10,000 students (1/3rd post-grad)
- 18 Nobel Prize winners
- Faculties of Natural Sciences, Engineering, Medicine, and Business School
- Highest research income in UK universities: £155 million p.a.; also highest industry funded research in the UK
- Total income: £410 million p.a.

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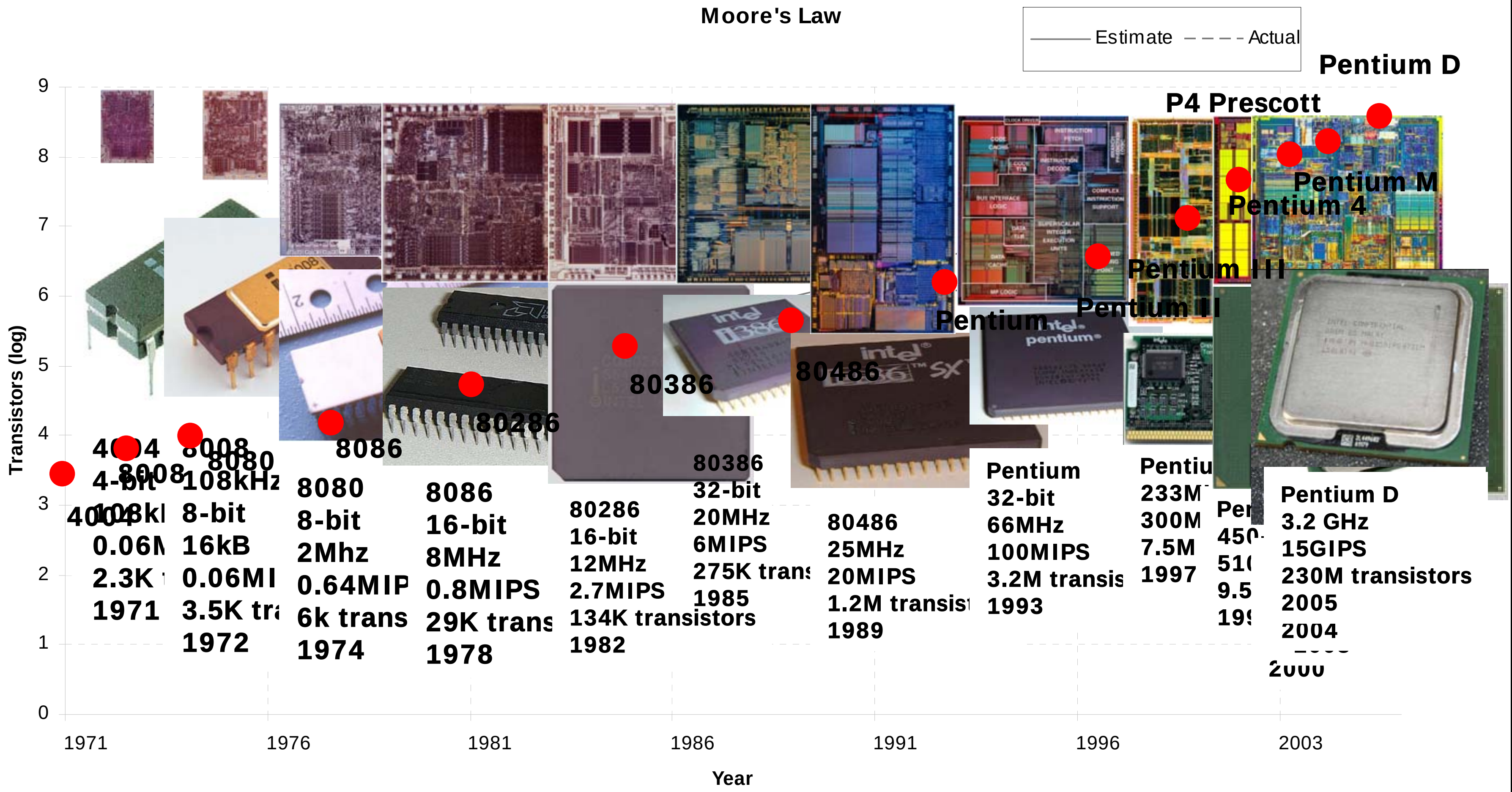
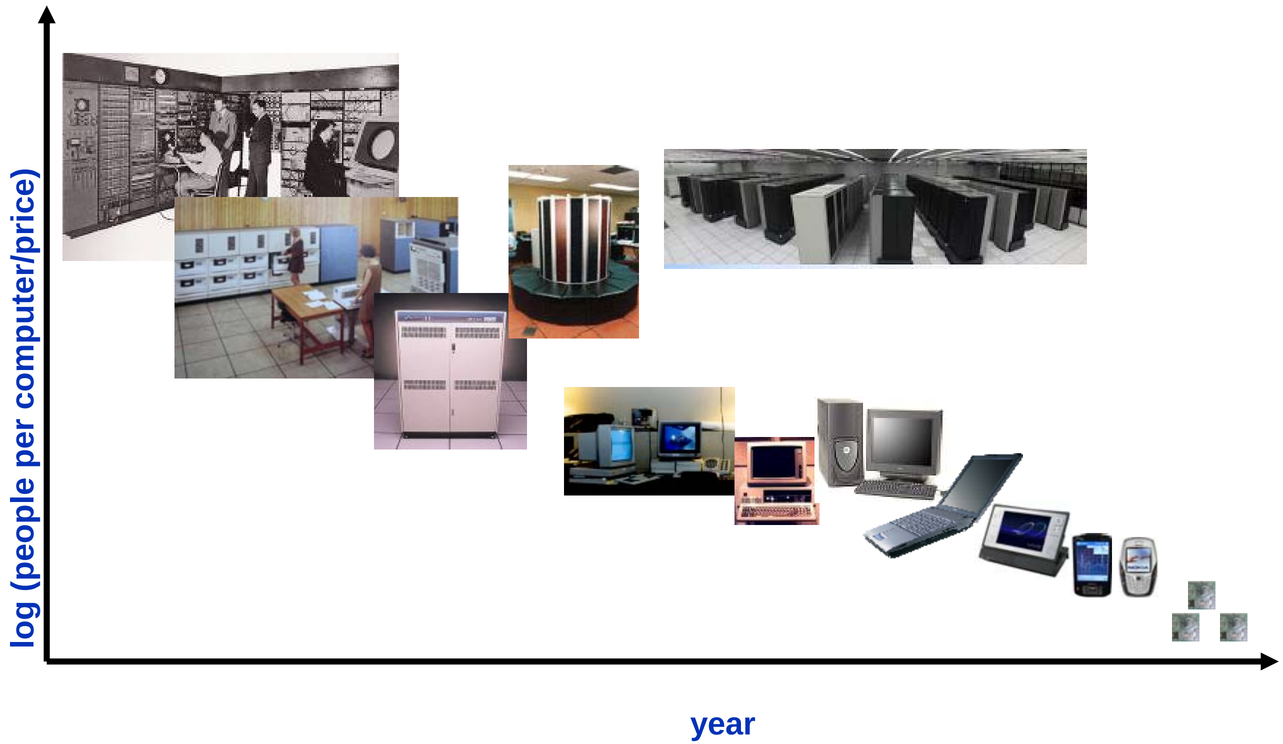
Evolution of computer technologies



http://velox.stanford.edu/group/chips_micropro_body.html
http://www.theregister.co.uk/2004/02/02/intel_prescott_90nm_pentium/
http://www.intel.com/products/processor/pentiumm/image.htm
http://www.pc-erfahrung.de/Index.html?ProzessormodelleIntelItanium2.html
http://www.pc-erfahrung.de/
http://www.granneman.com/
http://home.datacomm.ch/fmeyer/cpu/
http://trillian.randomstuff.org.uk/~stephen/history

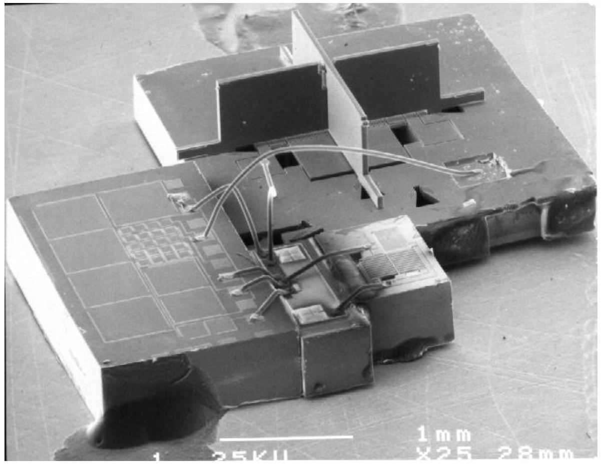
Evolution of computer technologies

- Bell's Law
  - New computing class every decade
  - New applications and contents develop around each new class

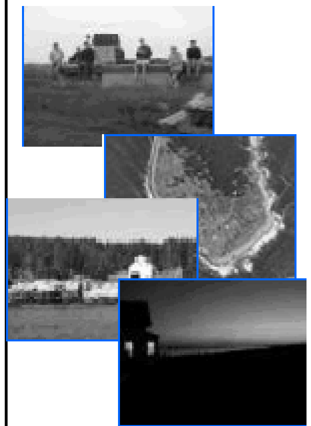


WSN – dust

- $11.7mm^3$
- Solar powered
- Bi-directional communications (laser light house)
- Sensing (acceleration and ambient light)



Habitat Monitoring:
Great Duck Island Study



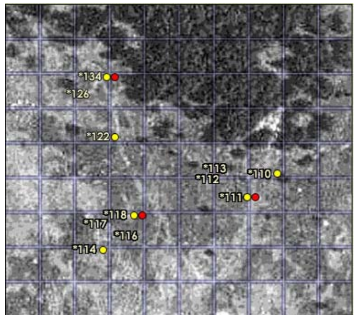
- In the spring 2002 and in August 2003, Intel Research Lab Berkeley deployed a large number of wireless sensor network nodes on Great Duck Island which monitors the microclimates in and around nesting burrows used by the Leach's Storm Petrel.

- Aimed to develop a habitat monitoring kit for non-intrusive and non-disruptive monitoring of sensitive wildlife and habitats.

- Each mote has a microcontroller, a low-power radio, memory and batteries.

- Temperature, humidity, barometric pressure, and mid-range infrared sensors were used.

- Motes periodically sample and relay their sensor readings to computer base stations on the island. These in turn feed into a satellite link that allows researchers to access real-time environmental data over the Internet.



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Location tracking:
MIT - Cricket

- **Cricket** is indoor location system for pervasive and sensor-based computing environments
- Ultrasound sensors are integrated with motes for tracking objects and activities
- Provides location information – identify space, position, coordinates and orientation of the subject – to applications running on handhelds, laptops, and sensor nodes
- Intended for indoor usage where outdoor systems like GPS wouldn’t work

Structural Health Monitoring:
Golden gate bridge study

- Golden gate bridge is exposed to strong wind and earth quake
- Budget for structural monitoring ~US$1,000,000
- Accelerometers are used to monitoring the vibration on the bridge and temperature sensors are integrated to calibrate the accelerometer against temperature difference




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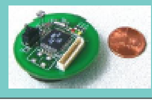
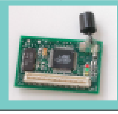
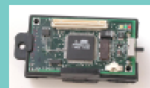
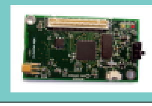
Mote Evolution

Mote Type Year	*WeC* 1998	*René* 1999	*René 2* 2000	*Dot* 2000	*Mica* 2001	*Mica2Dot* 2002	*Mica 2* 2002	*Telos* 2004
								
Microcontroller								
Type	AT90LS8535		ATmega163		ATmega128			TI MSP430
Program memory (KB)	8		16		128			60
RAM (KB)	0.5		1		4			2
Active Power (mW)	15		15		8		33	3
Sleep Power (μW)	45		45		75		75	6
Wakeup Time (μs)	1000		36		180		180	6
Nonvolatile storage								
Chip	24LC256				AT45DB041B			ST M24M01S
Connection type	I^2C				SPI			I^2C
Size (KB)	32				512			128
Communication								
Radio	TR1000				TR1000	CC1000		CC2420
Data rate (kbps)	10				40	38.4		250
Modulation type	OOK				ASK	FSK		O-QPSK
Receive Power (mW)	9				12	29		38
Transmit Power at 0dBm (mW)	36				36	42		35
Power Consumption								
Minimum Operation (V)	2.7		2.7		2.7			1.8
Total Active Power (mW)	24				27	44	89	41
Programming and Sensor Interface								
Expansion	none	51-pin	51-pin	none	51-pin	19-pin	51-pin	10-pin
Communication	IEEE 1284 (programming) and RS232 (requires additional hardware)							USB
Integrated Sensors	no	no	no	yes	no	no	no	yes

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Wireless and Body Sensor Networks

WSN

- Cover the environment
- Large number of nodes
- Multiple dedicated sensors
- Lower accuracy
- Small size not limiting factor
- Resistant to weather,
- Resistant to noise
- Resistant to asynchrony
- Early adverse event detection
- Failure reversible
- Fixed structure

BSN

- Cover the human body
- Fewer sensor nodes
- Single multitasking sensors
- Robust & Accurate
- Miniaturization
- Pervasive
- Predictable environment
- Motion artefacts an issue
- Early adverse event detection
- Failure irreversible
- Variable structure

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Wireless and Body Sensor Networks

WSN	BSN
Low level security	High security
Accessible power supply	Inaccessible power source
High power demand	Lower power availability
Solar,wind power	Thermal, piezoelectric energy
Replaceable/disposable	Biodegradeable
No biocompatibility needed	Biocompatible
Low context awareness	High context awareness
Wireless solutions available	Lower power wireless
Data loss less of an issue	Sensitive to data loss

Focus of This Talk

- Technical Challenges and Opportunities of BSN
- Healthcare and Wellbeing Monitoring
- Sports and Entertainment
- Conclusions

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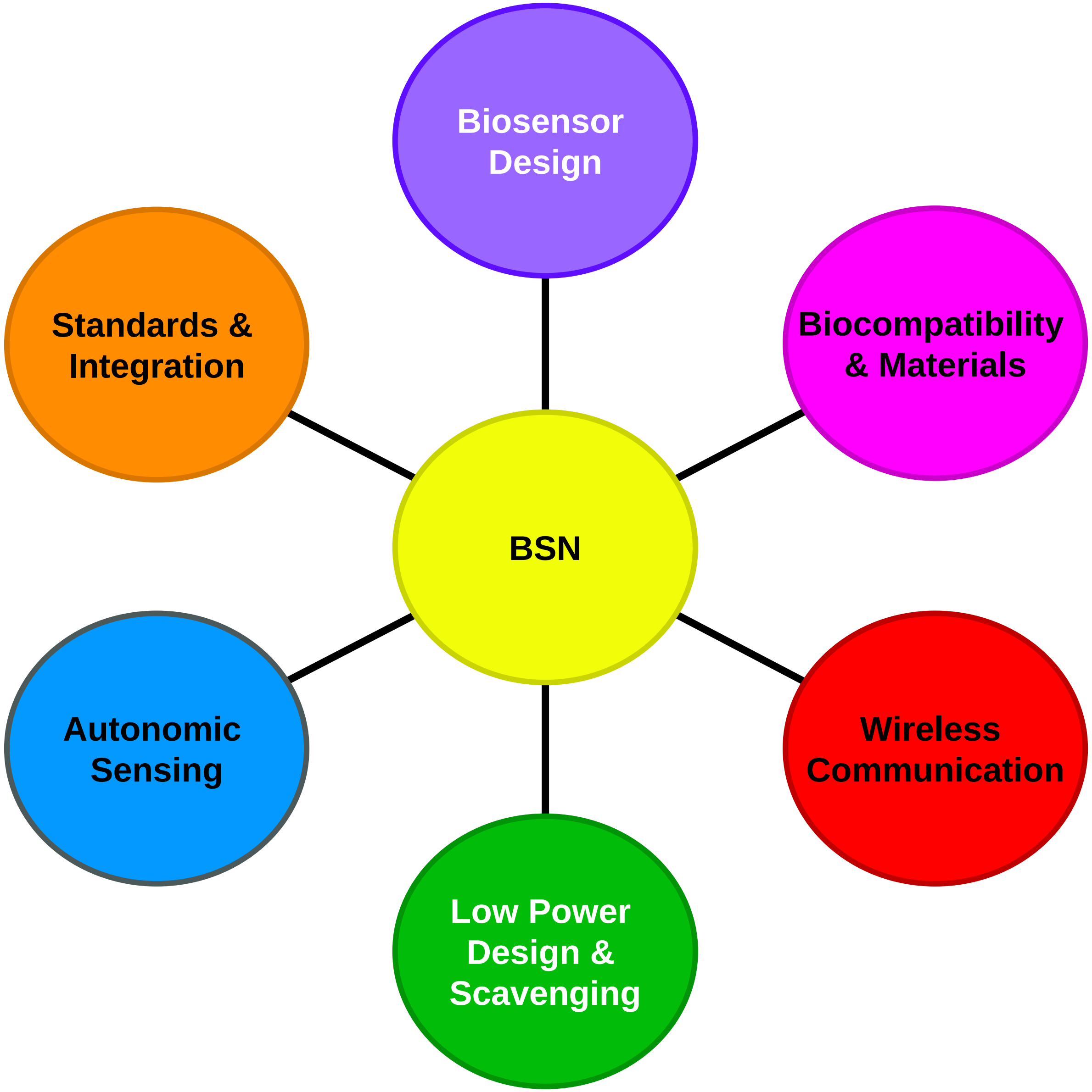
What does BSN Cover?



Biocompatibility and Materials

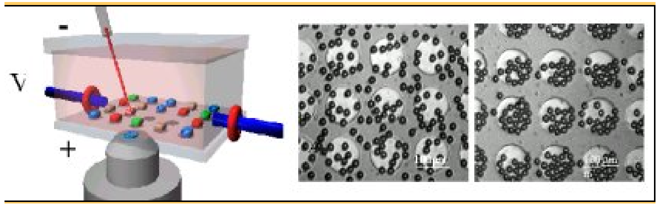
- **Biosensors**

Implant blood pressure
flow sensor (CardioMEMS)

- **Stents**

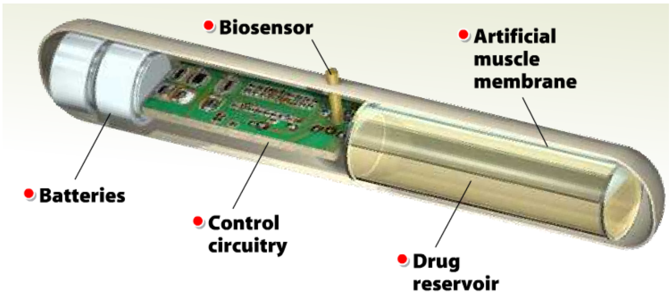
Drug releasing stents -
Taxus stents - Boston Scientific Co.

- **Tissue Engineering**
  - Pattern and manipulate cells in micro-array format



Ozkan et. al (2003), Langmuir

- **Drug delivery systems**



Smart Pill – Sun-Sentinel Co.

Carol Ezzell Webb, “Chip Shots”, IEEE Spectrum Oct 2004

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Biosensor Design

- Thermistor
- ECG
- SpO_2
- Glucose concentration

Thermistor
(ACR system)

Implant ECG recorder
(Medtronics –Reveal)

Oxymeter
(Advanced Micronics)

Glucose sensor
(Glucowatch)

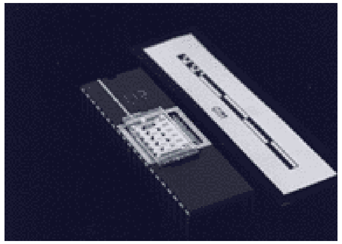
Implant blood pressure
flow sensor (CardioMEMS)

Implant pH sensor
(Metronics – Bravo)

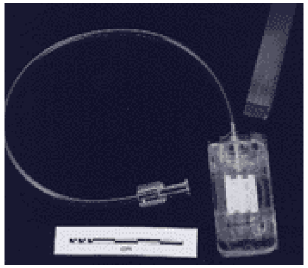
Pill-sized camera
(Given Imaging)

MEMS - Microelectromechanical System

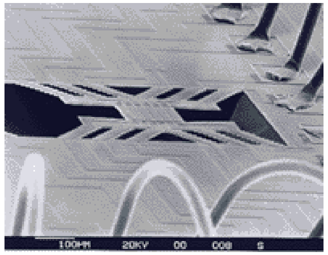
- Integrated micro devices or systems combining electrical and mechanical components
- Fabricated using integrated circuit (IC) batch processing techniques
- Size range from micrometers to millimetres
- Applications includes: accelerometers, pressure, chemical and flow sensors, micro-optics, optical scanners, and fluid pumps



Tactile Sensor for Endoscopic Surgery (SFU)



Pressure sensor for clinical use (SFU)



CMOS Micromachined Flow Sensor (SFU)

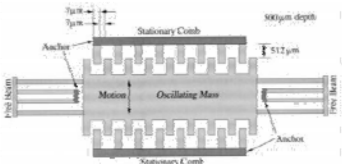
Power Scavenging

- **Photovoltaics (Solar cells)**
  - 15-20% efficiency (single crystal silicon solar cell)
  - 15mW/cm^2 (midday outdoor) to 10µW/cm^2 (indoors)
- **Temperature Gradients**
  - 1.6% efficiency (at 5^{o}C above room temperature)
  - 40 µW/cm^2 (5^{o}C differential, 0.5cm^2, and 1V output)
- **Human Power**
  - Human body burns 10.5MJ/day (average power dissipation of 121W)
  - 330 µW/cm^2 (piezoelectric shoe)
- **Wind/Air Flow**
  - 20-40% efficiency (windmills, with wind velocity 18mph)
- **Vibrations**
  - Electromagnetic, electrostatic, and piezoelectric devices
  - 200 µW (1cm^3 power converter with vibration of 2.25 m/s^2 at 120Hz)
- **Nuclear microbatteries**
  - With 10 milligrams of polonium-210, it can produce 50mW for more than 4 months
  - It can safely be contained by simple plastic package, as Nickel-63 or tritium can penetrate no more than 25 mm

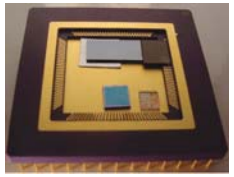
Panasonic BP-243318

Applied Digital Solutions – thermoelectric generator

MIT Media Lab



MIT – MEMS piezoelectric generator

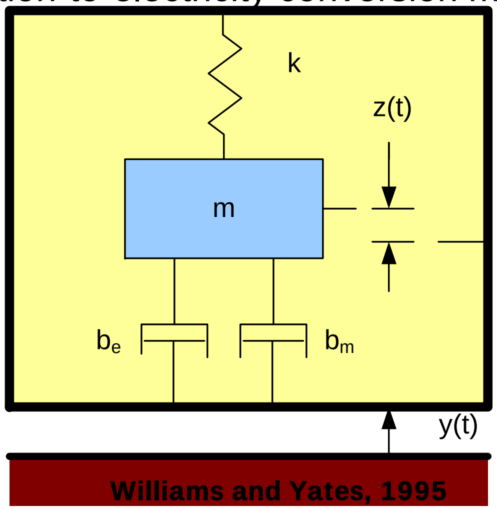


Cornell University - Nuclear micro-generator **(with a processor and a photo sensor)**

Power Scavenging

- Kinetic energy of vibrating mass to electrical power

Vibration-to-electricity conversion model



$$m\ddot{z} + (b_e + b_m)\dot{z} + kz = -m\ddot{y}$$

where z is the spring deflection, y is the input displacement, m is the mass, b_e is the electrically induced damping coefficient, b_m is the mechanical damping coefficient, and k is the spring constant

- Power converted to the electrical system is equal to the power removed from the mechanical system by b_e, the electronically induced damping.

$$P = \frac{1}{2} b_e \dot{z}^2 \qquad |P| = \frac{m\zeta_e \omega^3 Y^2}{4\zeta_T^2}$$

where Y is the Laplace transform of input displacement acceleration magnitude of input vibration, w is the frequency of the driving vibrations, ζ_e is the electrical damping ratio, ζ_m is the mechanical damping ratio, and $\zeta_T = \zeta_e + \zeta_m$

S.Roundy, P. Wright and J. Rabaey, *Energy Scavenging for Wireless Sensor Networks*, Kluwer Academic Publishers, 2004.

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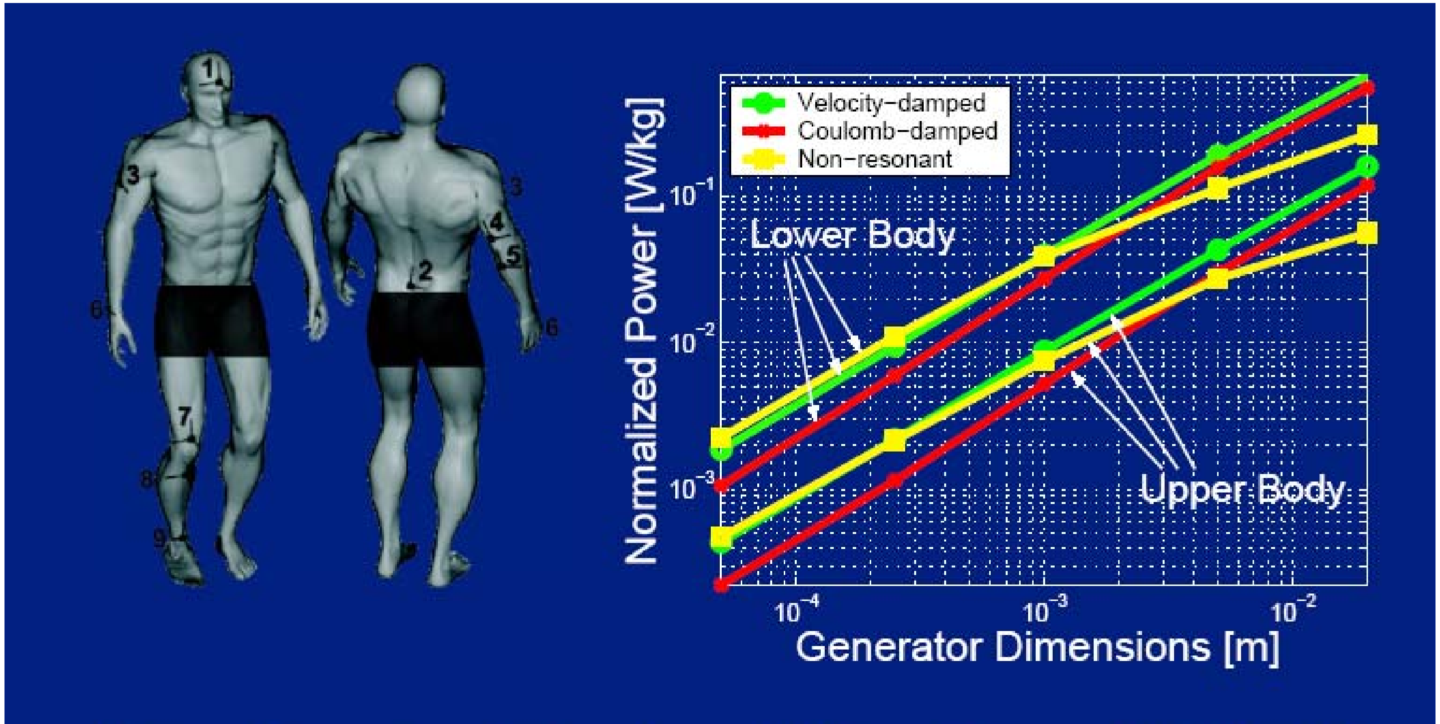
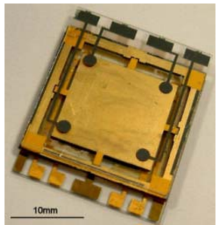
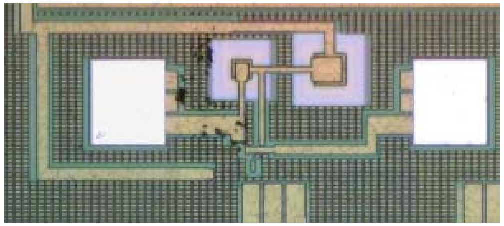
Human Power Generation

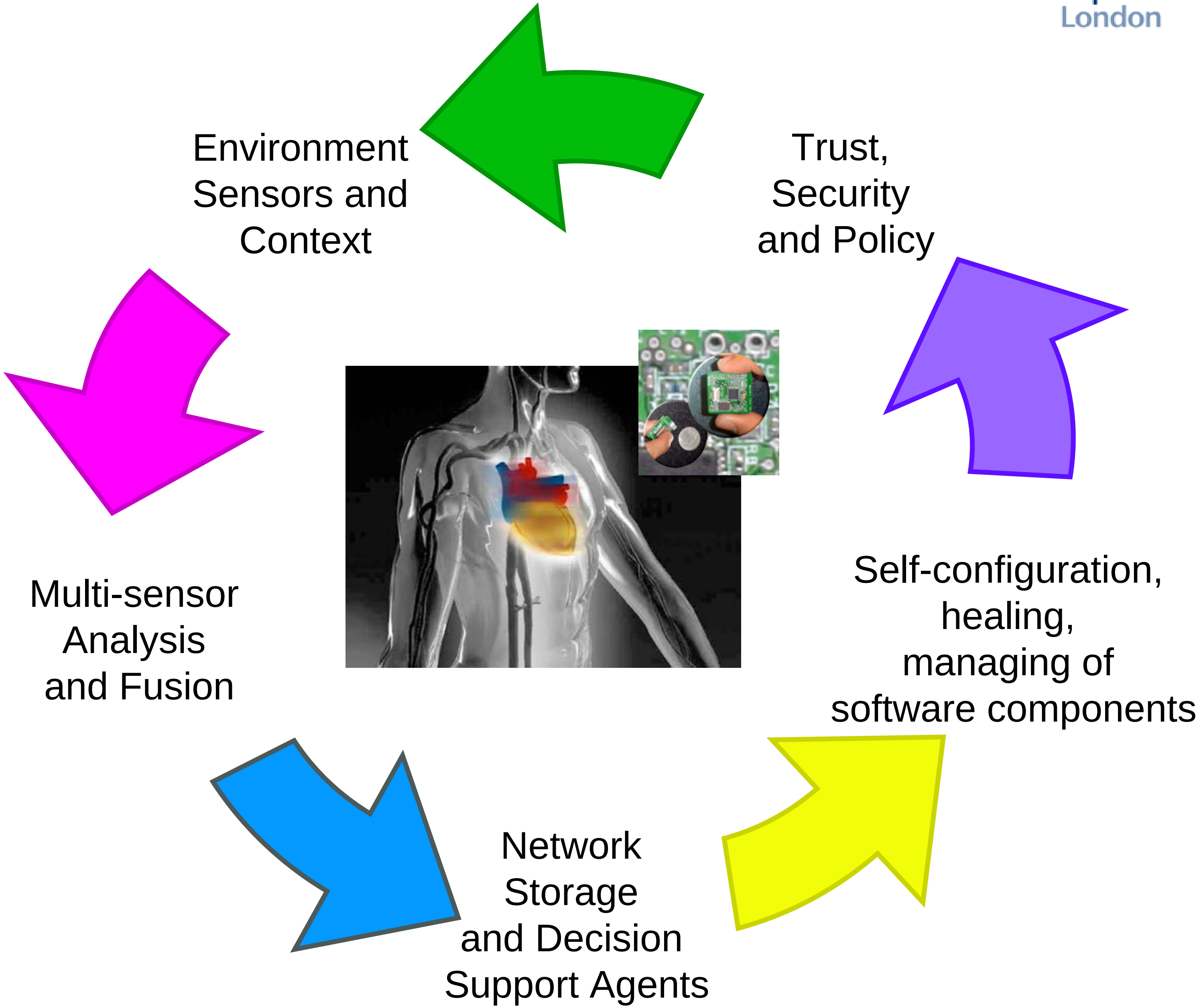


This work was in collaboration with T. von Büren at ETH Zurich





Mitcheson, Yates, Yeatman, Green and Holmes, BSN 2005



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Wearable pulse oximetry

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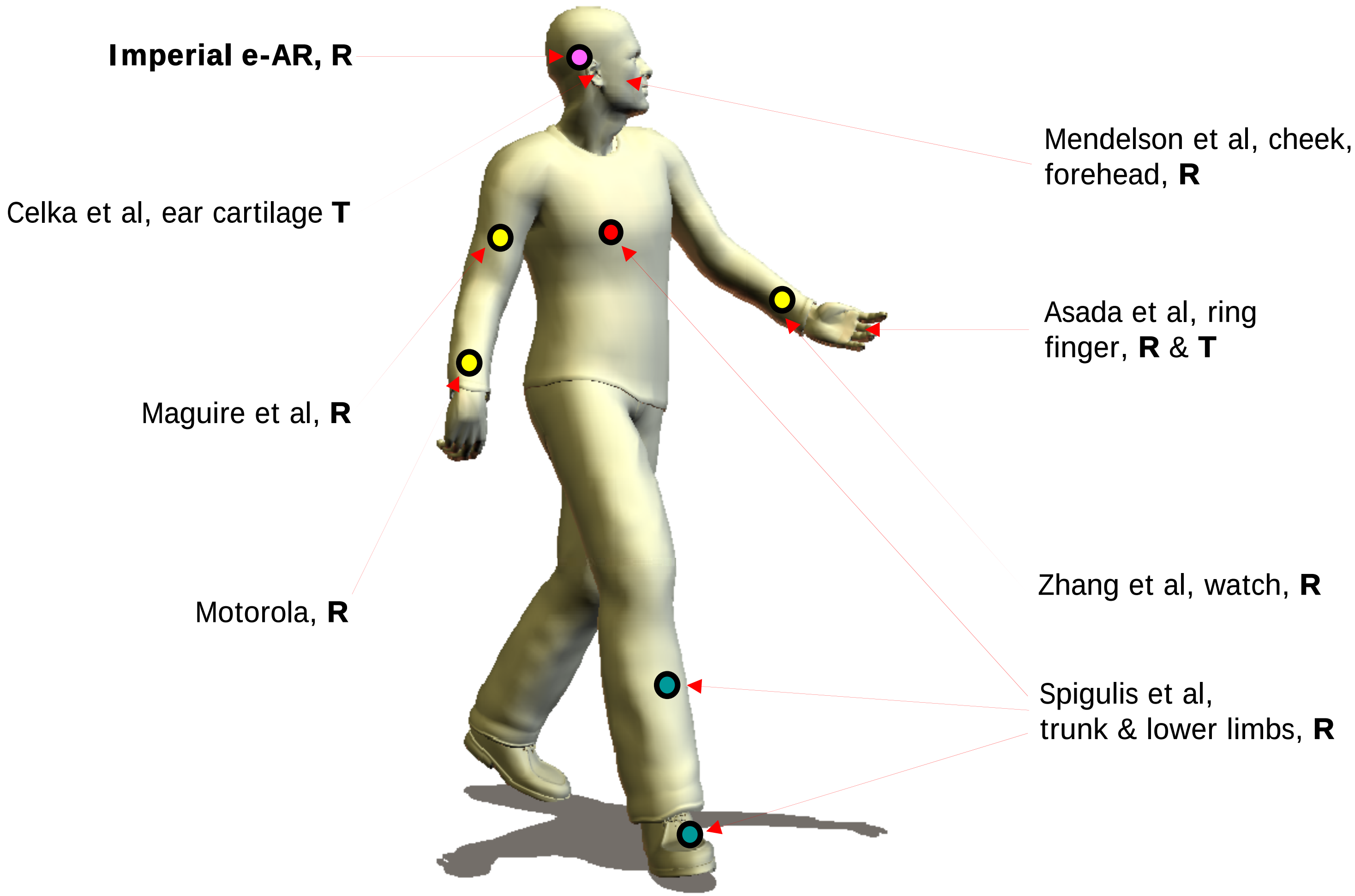
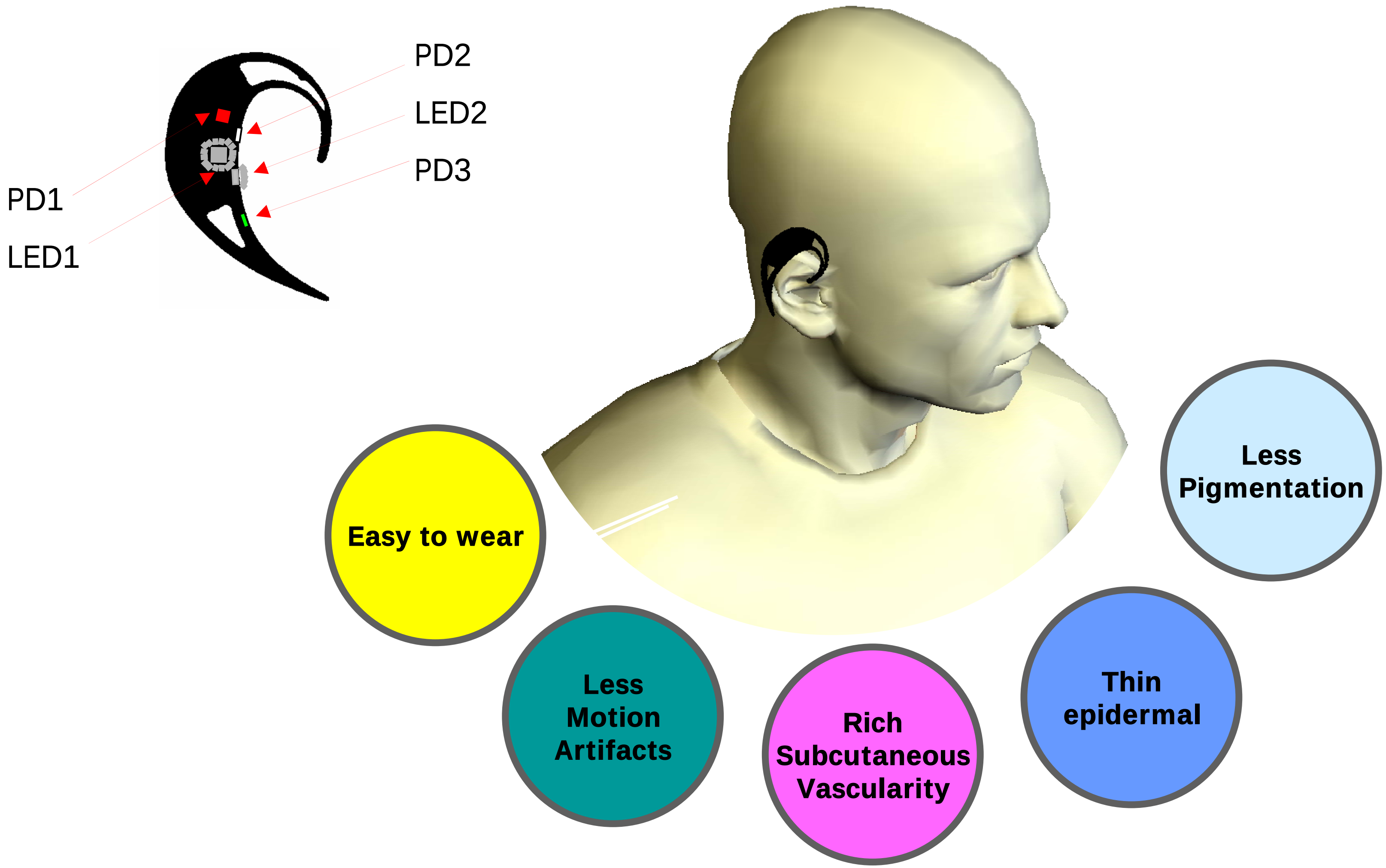


Sensor Deployment



Guang-Zhong Yang, Lei Wang, BSN 2007

Skin PPG

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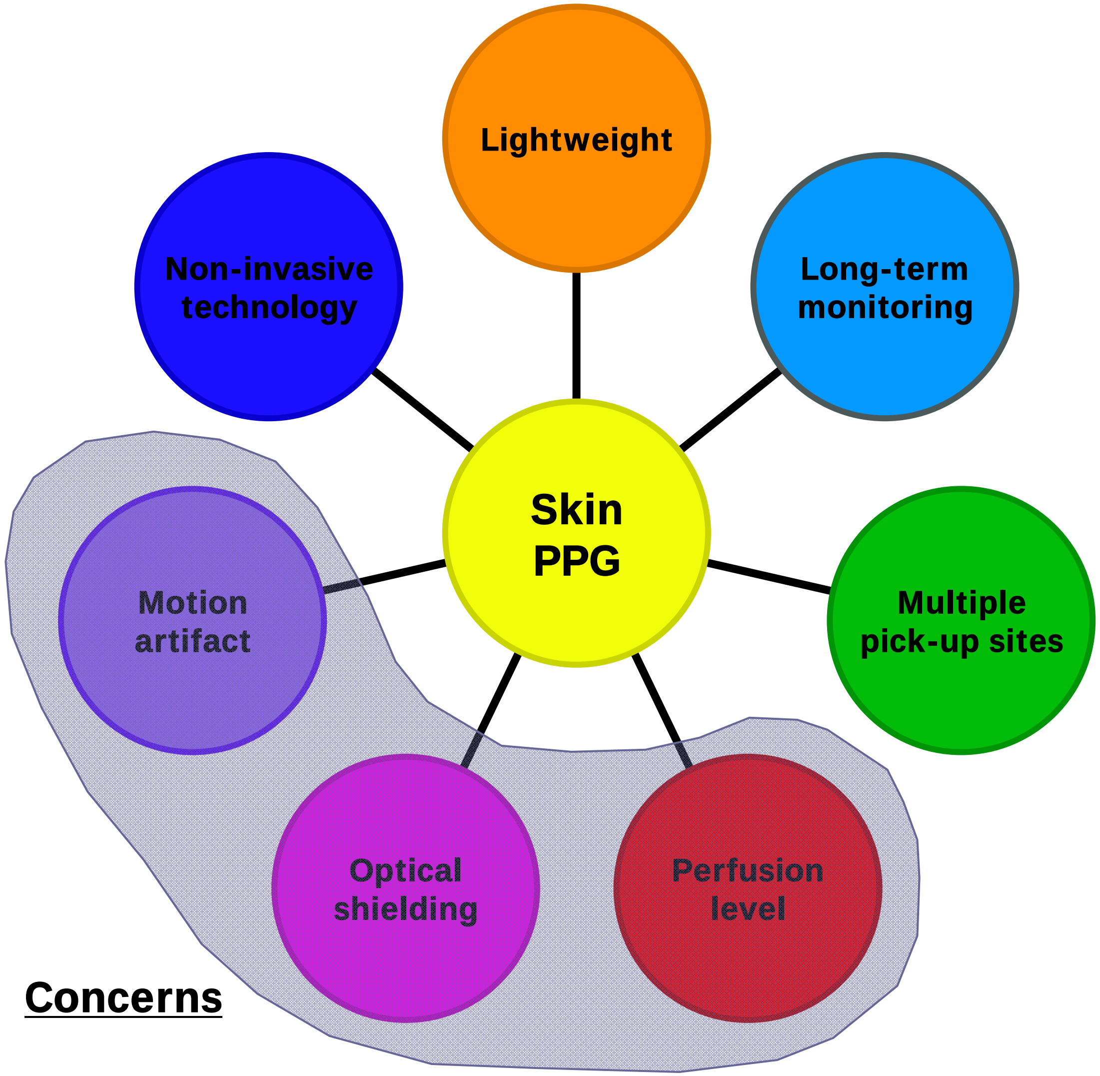

Earpiece PPG

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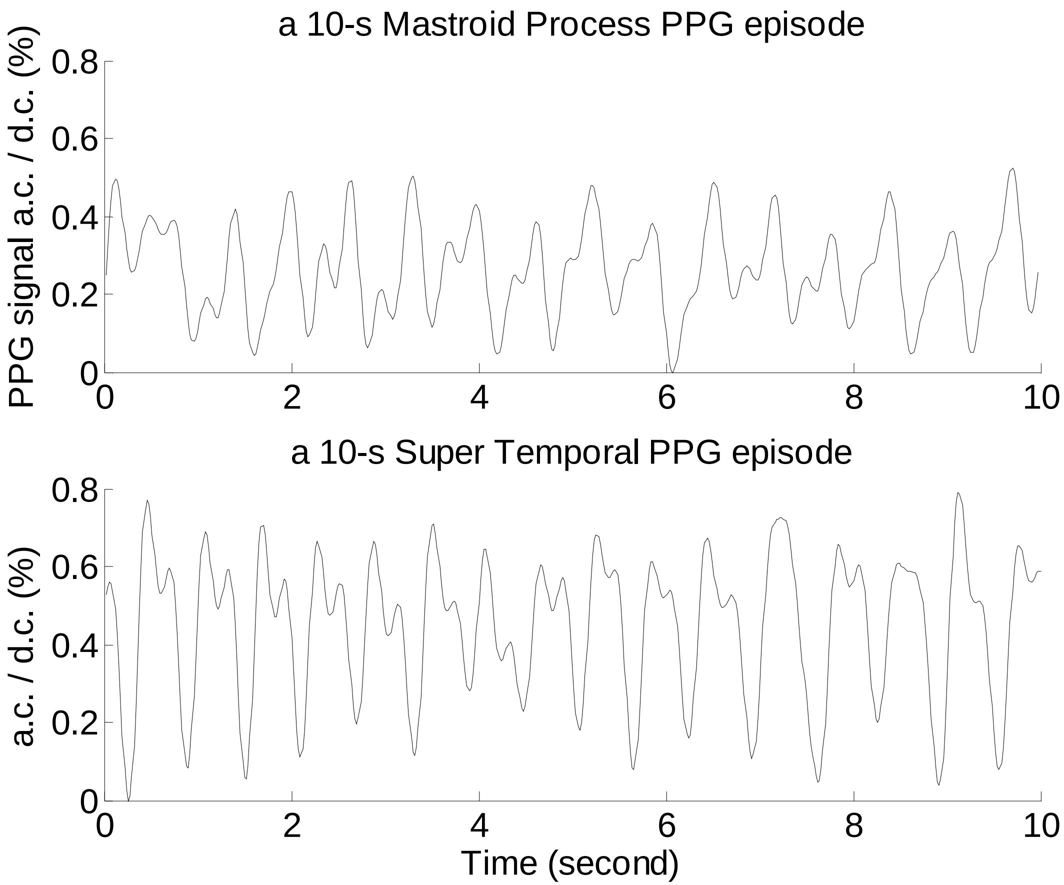
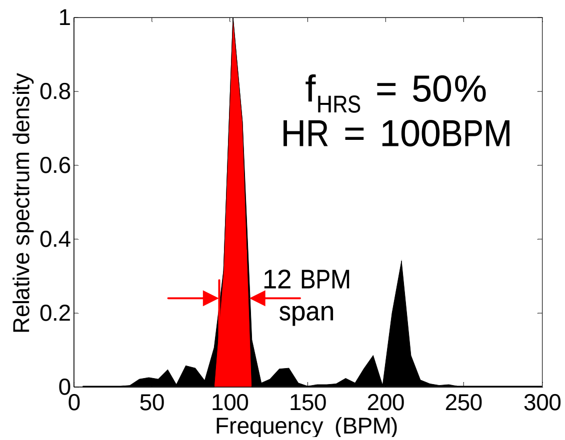


Fidelity Index

$$f_{HRS} = P_{span} / P_{all}$$



- Verified by multiple subjects at various resting states including sitting, standing and reading.
- a.c. / d.c. ratio 0.001 - 0.01 and 10% relative signal strength.

Guang-Zhong Yang, Lei Wang, et al BSN 2007

Dynamic Heart Rate

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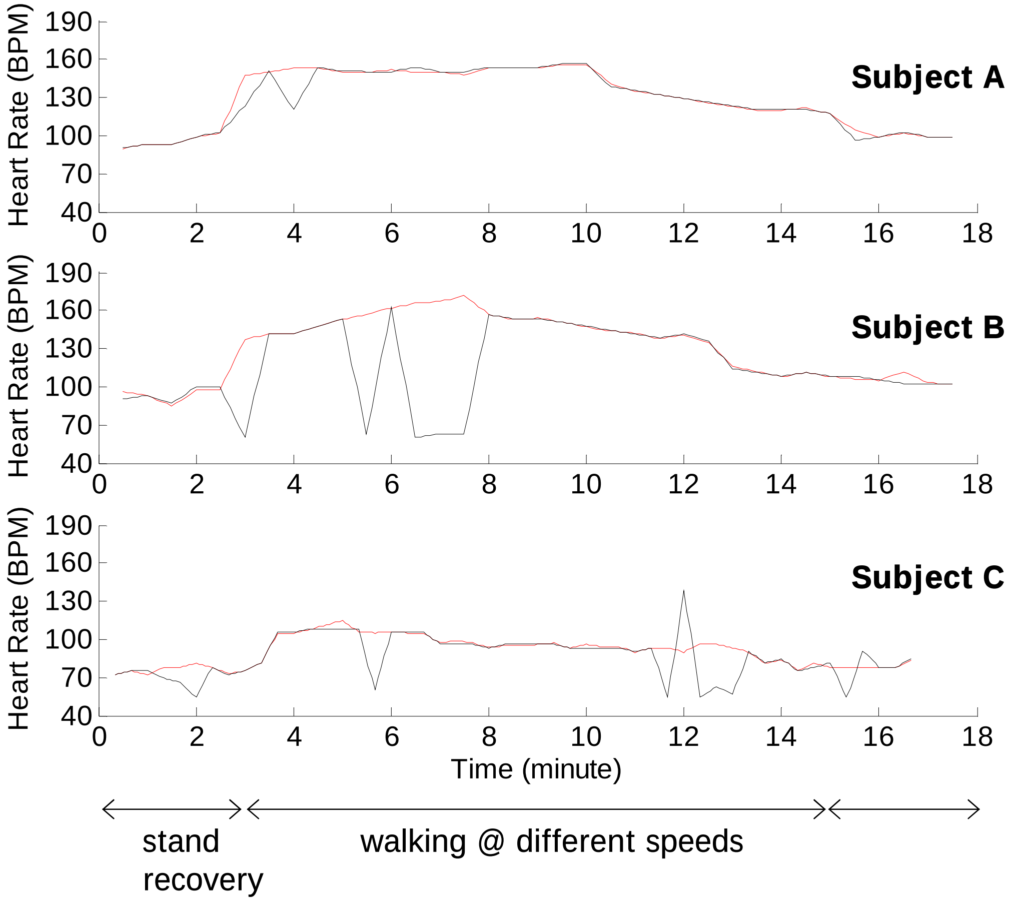

- Overall 80% sucessful rate for exercise heart rate detections.
- For some subjects, heart rates were detectable even during maxium exercise load.
- The dynamic heart rates helped identifying different exercise stages and retrieving the recovery period.

Guang-Zhong Yang, Lei Wang, et al BSN 2007

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The Need for Autonomic and Cognitive Sensing

- The essence of autonomic computing is to develop self-management systems and free human from complicated administration tasks.

- The eight characteristics of an autonomic system include:
  - Self-management
  - Self-configuration
  - Self-integration
  - Self-protection
  - Self-optimisation
  - Self-healing
  - Self-adaptation
  - Self-scaling

Example probabilistic models for activity recognition

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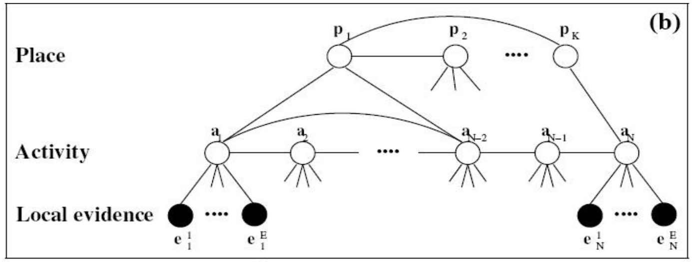
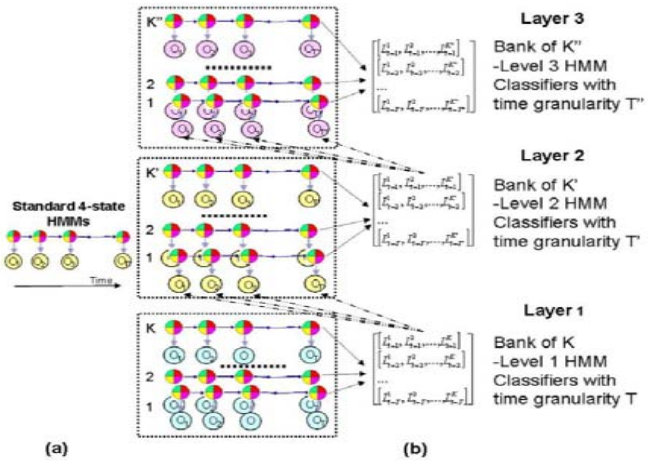


Hierarchical activity models with GPS and Relational Markov Networks

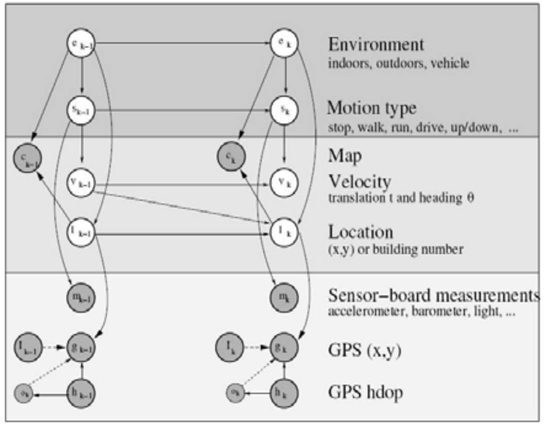
[Location based Activity Recognition. L.Liao, D. Fox and H. Kautz NIPS '05

Layered HMMs with microphone, camera, mouse and keyboard for office activities



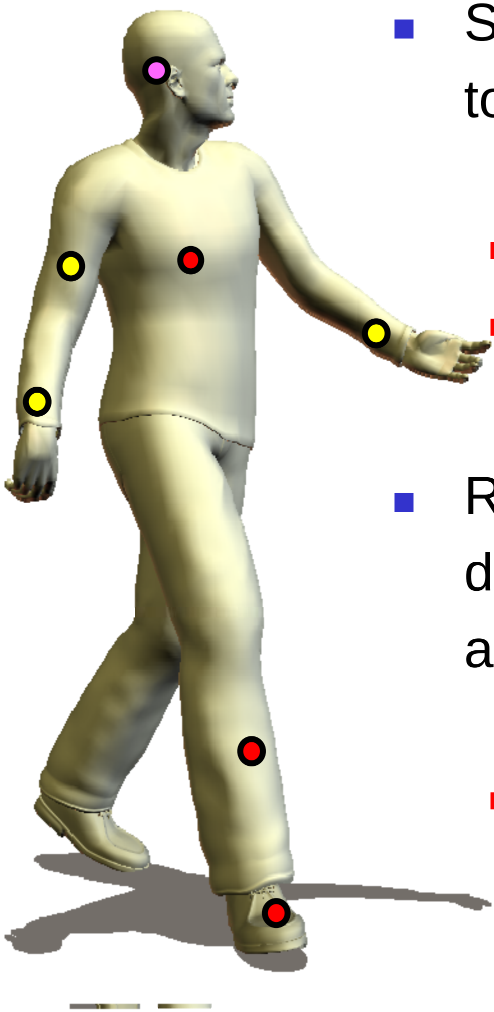
Layered Representation for Human Activity Recognition. N. Oliver, E. Horvitz, A. Garg (CVIU 2002)
A Comparison of Dynamic HMM and Dynamic Bayesian Nets for Recognising Office Activities.
N. Oliver and E. Horvitz (UM05)

Dynamic Bayesian Model with data from wearable sensors and GPS.



Recognizing Activities and Spatial Context using Wearable Sensors.
A. Subramanya,A. Raj, J. Bilmes, D.Fox, UAI 06

Basic Concepts



- Some sensors are more informative with regard to certain activities than others.
  - lower limbs → sitting, standing, walking
  - upper limbs → typing, hand shaking
- Reasoning about different activities requires different sets of sensors at different locations and time.
  - Change in information availability as user moves through static ambient sensors.

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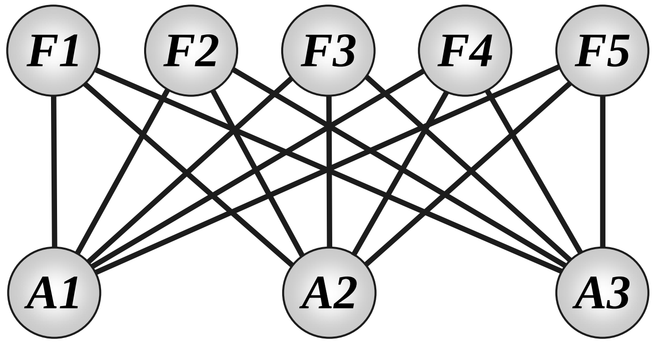
Feature Selection

- Feature selection is used for learning the structure of the proposed distributed model.
  - To reduce computational complexity while maintaining accuracy (self-optimising)
  - To identify features that are relevant to each class.



Initial Dependency Graph

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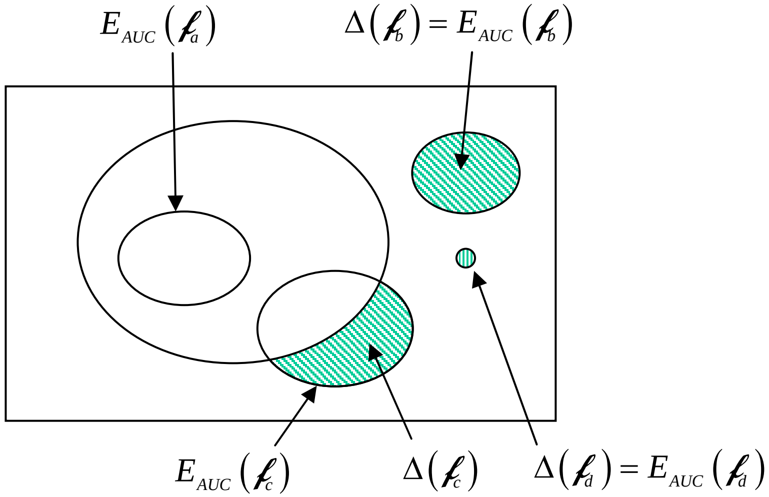
Feature Redundancy

- Redundancy can be used to improve the reliability and fault tolerance of the model (self-healing property)

- With new objective function, irrelevant features is removed before redundant features.

$$\mathrm{D}_r\left(\boldsymbol{f}_i\right) = \left(1-\omega_1\right)\times\left(E_{AUC}\left(\boldsymbol{\mathcal{G}}^{(k)}\right) - E_{AUC}\left(\boldsymbol{\mathcal{G}}^{(k)} - \left\{\boldsymbol{f}_i\right\}\right)\right) + \omega_1 \times E_{AUC}\left(\boldsymbol{f}_i\right)$$



a measure of redundancy

Guang-Zhong Yang, Surapa Thiemajarus
Bodynet 2007a

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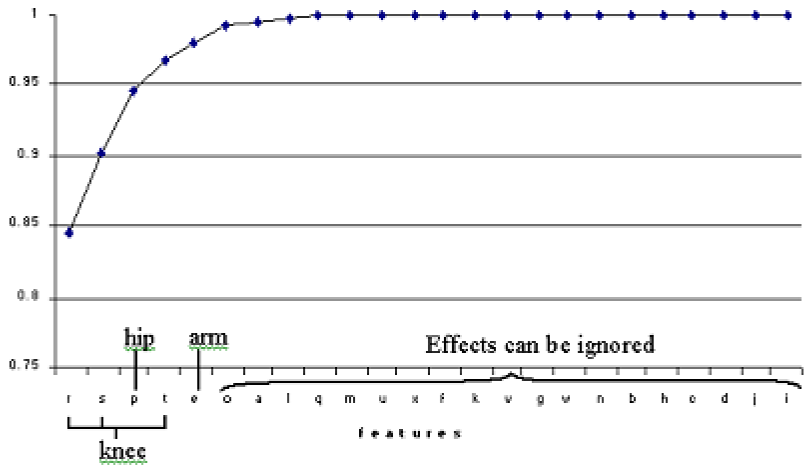
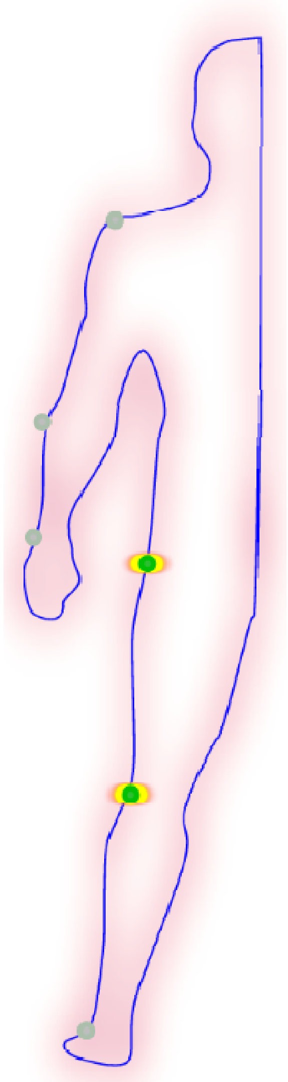
Feature selection for BSN

- Experiments were performed on subsets of activities as follows:
  - Sitting, standing, and walking
  - Going up and downstairs
  - Handshaking, writing on white board and typing
- Feature selection for sitting, standing and walking:



Features	Mean	SD
All features	0.719	0.051
rspte	0.773	0.02
rspt	**0.824**	**0.011**
rsp	0.792	0.025
rs	0.782	0.039
r	0.781	0.026

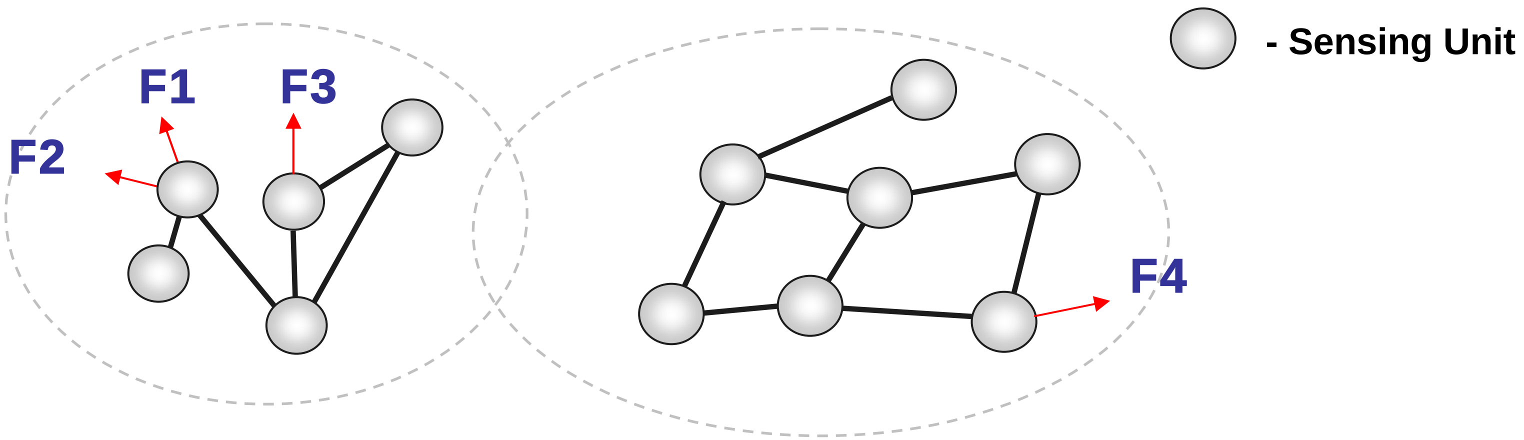
Average mean and standard deviation of the classification accuracy



UbiMon
www.ubimon.net

Model Complexity

- The cost of features can be estimated based on:
  - Number of features
  - Different levels of communication incurred:
    - Same sensor node
    - Different nodes, same subnet
    - Different subnets



$$Cost\left(\{F1, F2\}\right) < Cost\left(\{F1, F3\}\right) < Cost\left(\{F1, F4\}\right)$$

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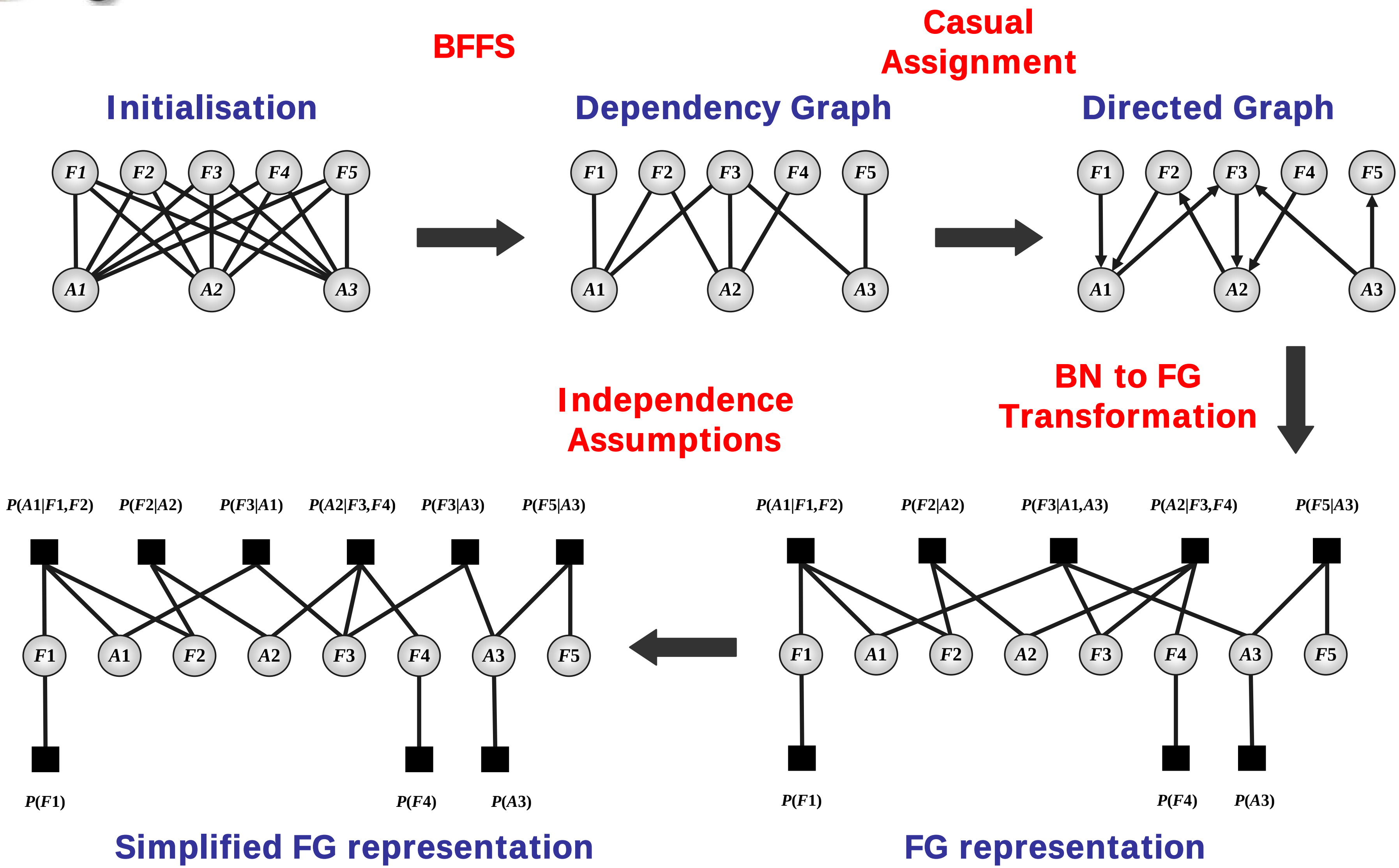
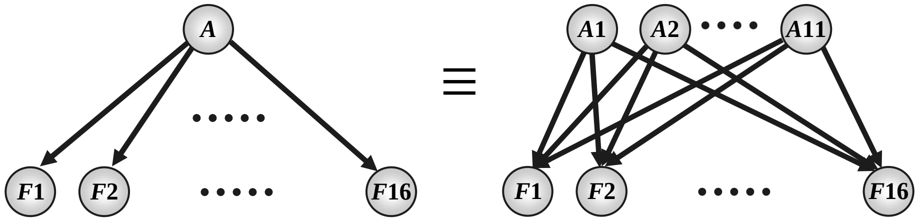
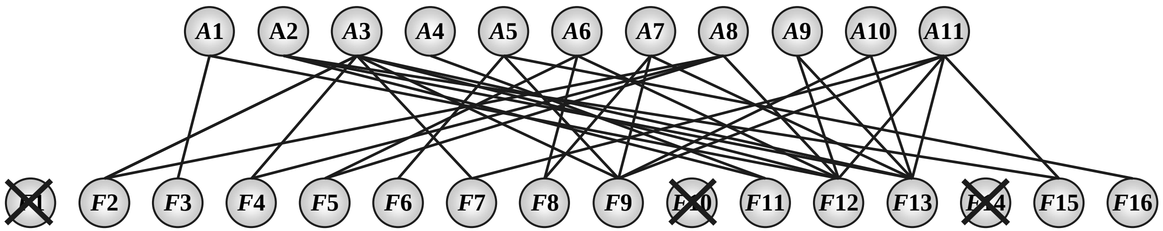
An Illustration of Model Construction



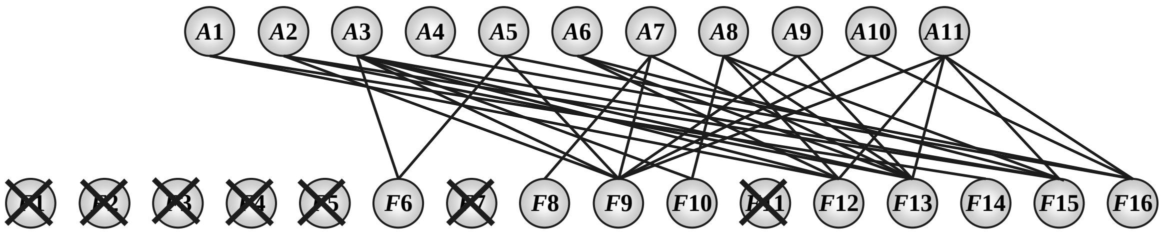
Experiments: Results (con't)



Model 2
Accuracy: 77.3%
#s of Links: 176
#s of Features: 16



Model 3
Accuracy: 66.28%
#s of Links: 34
#s of Features: 13



Model 4
Accuracy: 72.60%
#s of Links: 34
#s of Features: 9

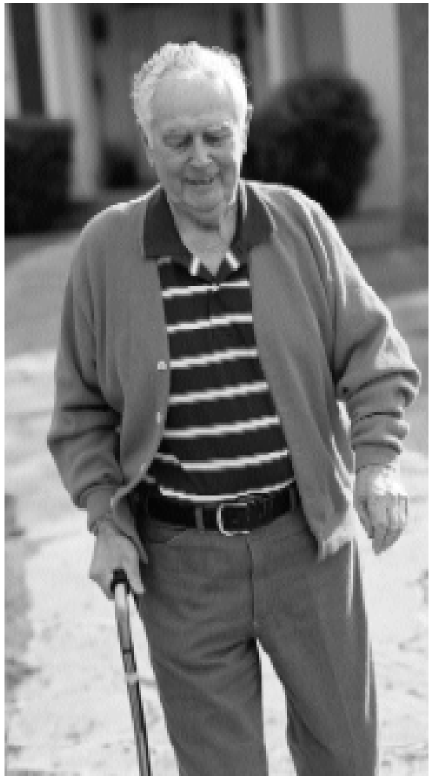
Guang-Zhong Yang, Surapa Thiemajarus Bodynet 2007

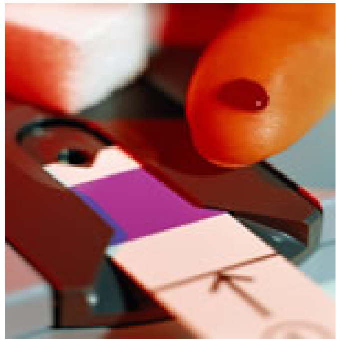
Focus of This Talk

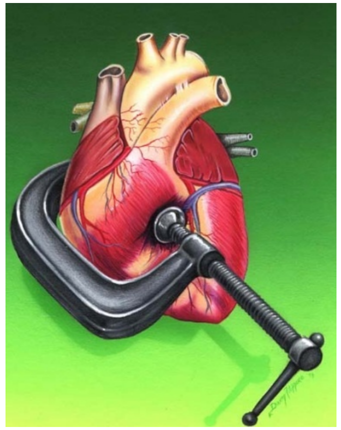
- Technical Challenges and Opportunities of BSN
- **Healthcare and Wellbeing Monitoring**
- Sports and Entertainment
- Conclusions

Drivers of Healthcare Applications

- Aging population
- Chronic disease
- Acute care
- Early diagnosis







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Driver 1: The Aging Population

- The *proportion of elderly people is likely to double* from 10% to 20% over the next 50 years.
- In the western world, the *ratio of workers to retirees is declining*.
- The number of *people living alone is rising*.
- **A change of care provision is needed for these patients.**


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Driver 2: Chronic Disease

- Ischemic heart disease
- Hypertension
- Diabetes
- Neuro-degenerative disease (Parkinsons, Alzheimers)
- Global deterioration (Dementias)

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Driver 3: Acute Disease

- Acute presentations
- Interventions
- Post elective care
- Post-operative monitoring

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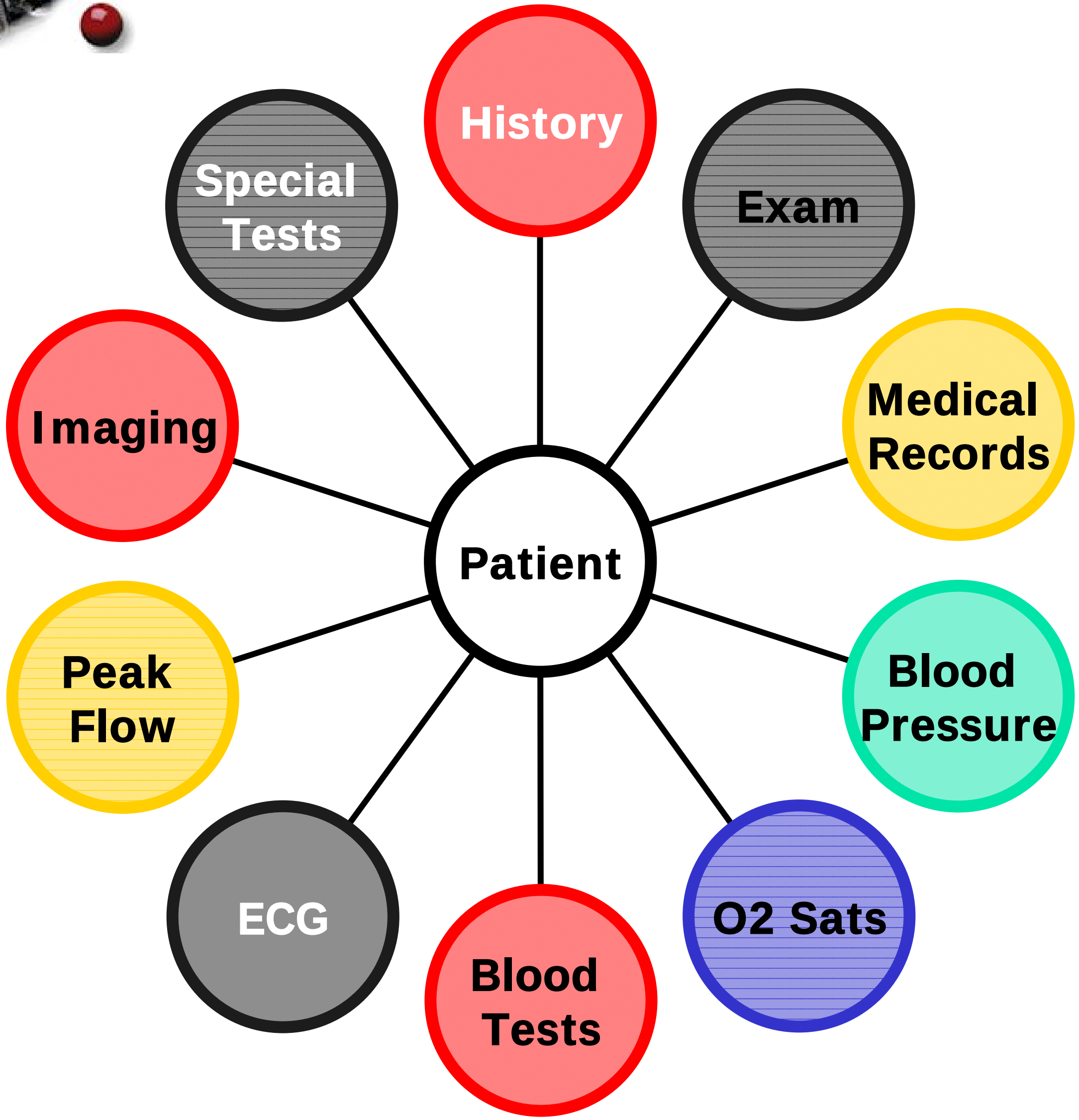
Driver 4: Diagnostics



Only a <u>SNAPSHOT</u> of a patient's health

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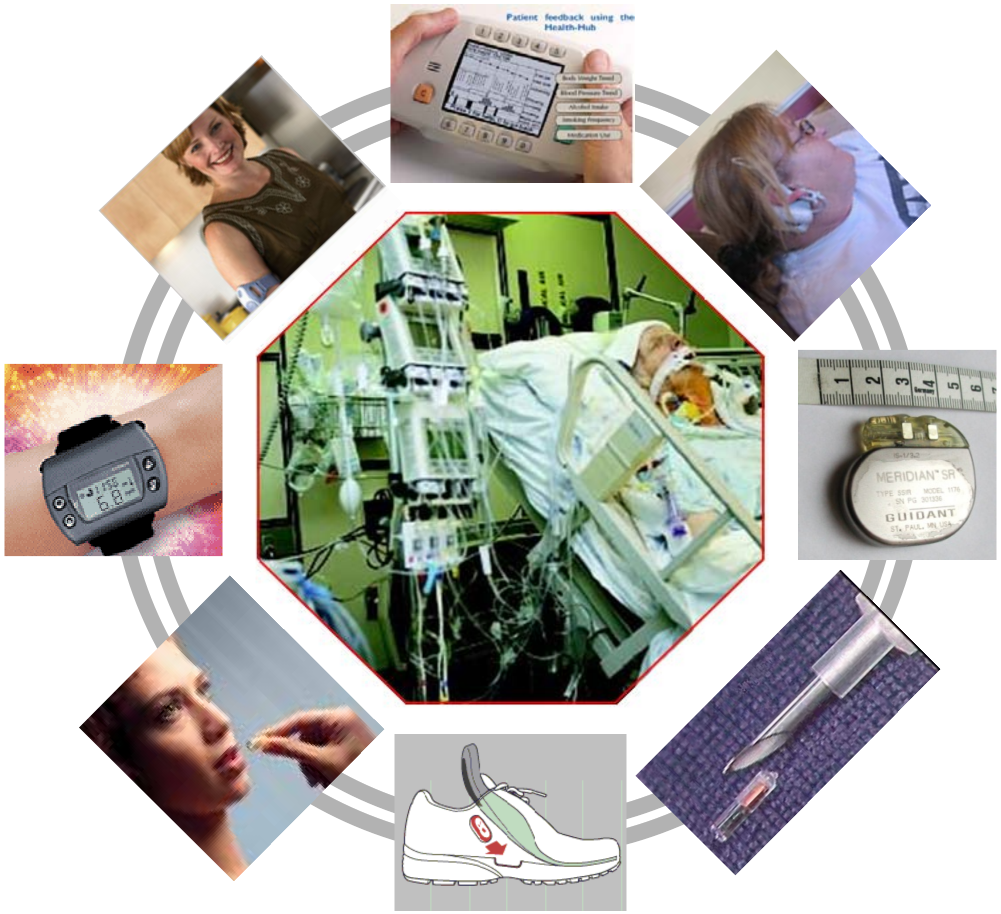
BSN for Healthcare



- Dynamic
- Continuous use 24/7
- Preventative
- Earlier diagnosis
- Home-based
- Post-operative monitoring
- Unobtrusive
- Minimal interventions
- Improving Quality-of-Life
- Anytime
- Anywhere
- Anybody

The ageing body

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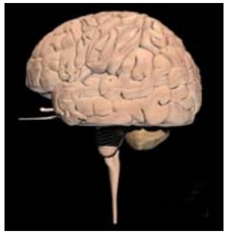
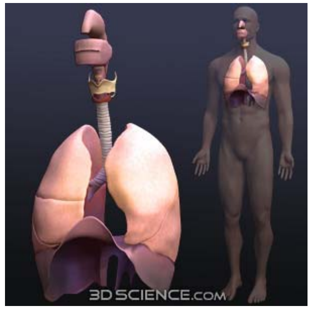
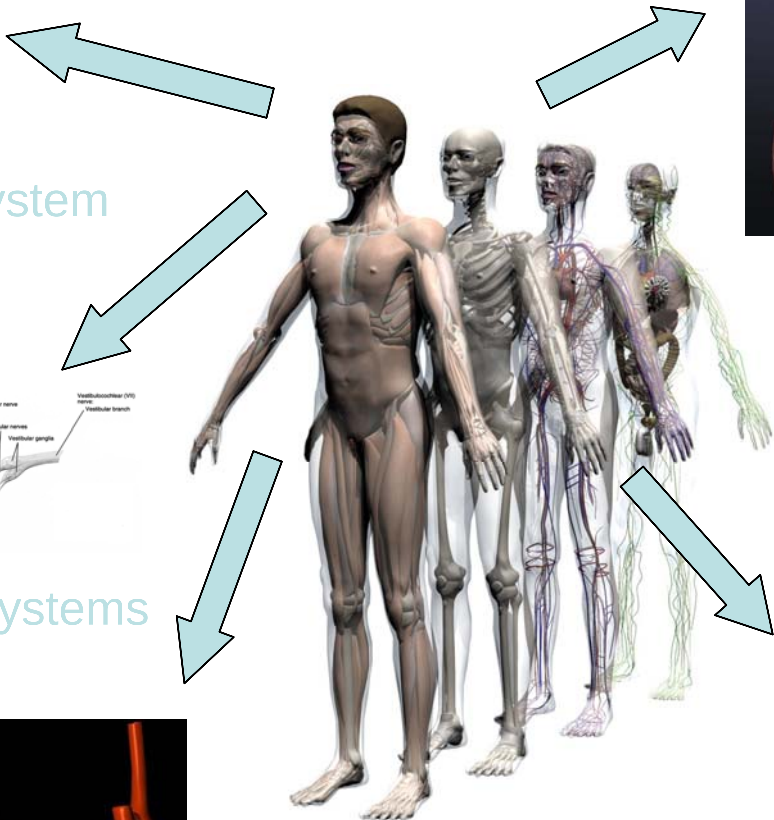
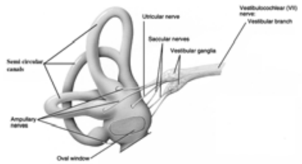


Brain and nervous system



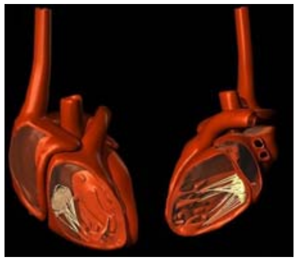
Respiratory system





Visual and sensory systems

Musculoskeletal system



Circulatory system

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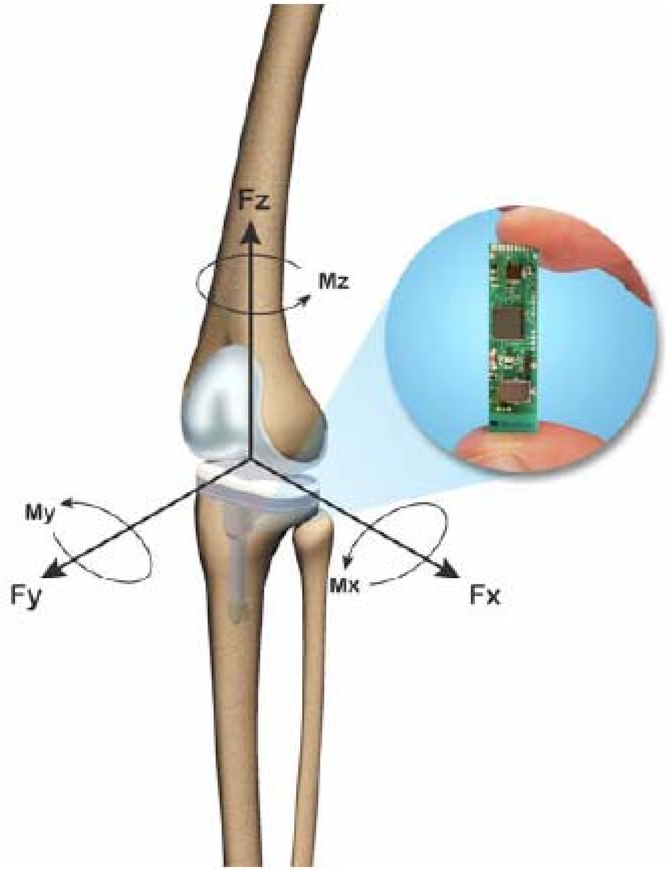
Implantable Sensors: Microstrain Inc

- Array of 12 piezoresistive strain gauges were embedded within the implant's tibial component.
- Integral miniature coil is used to harvest energy from an externally applied alternating field.
- A wireless antenna transmits digital sensor data to a computer
- 3-D Torque and force data obtained from implant



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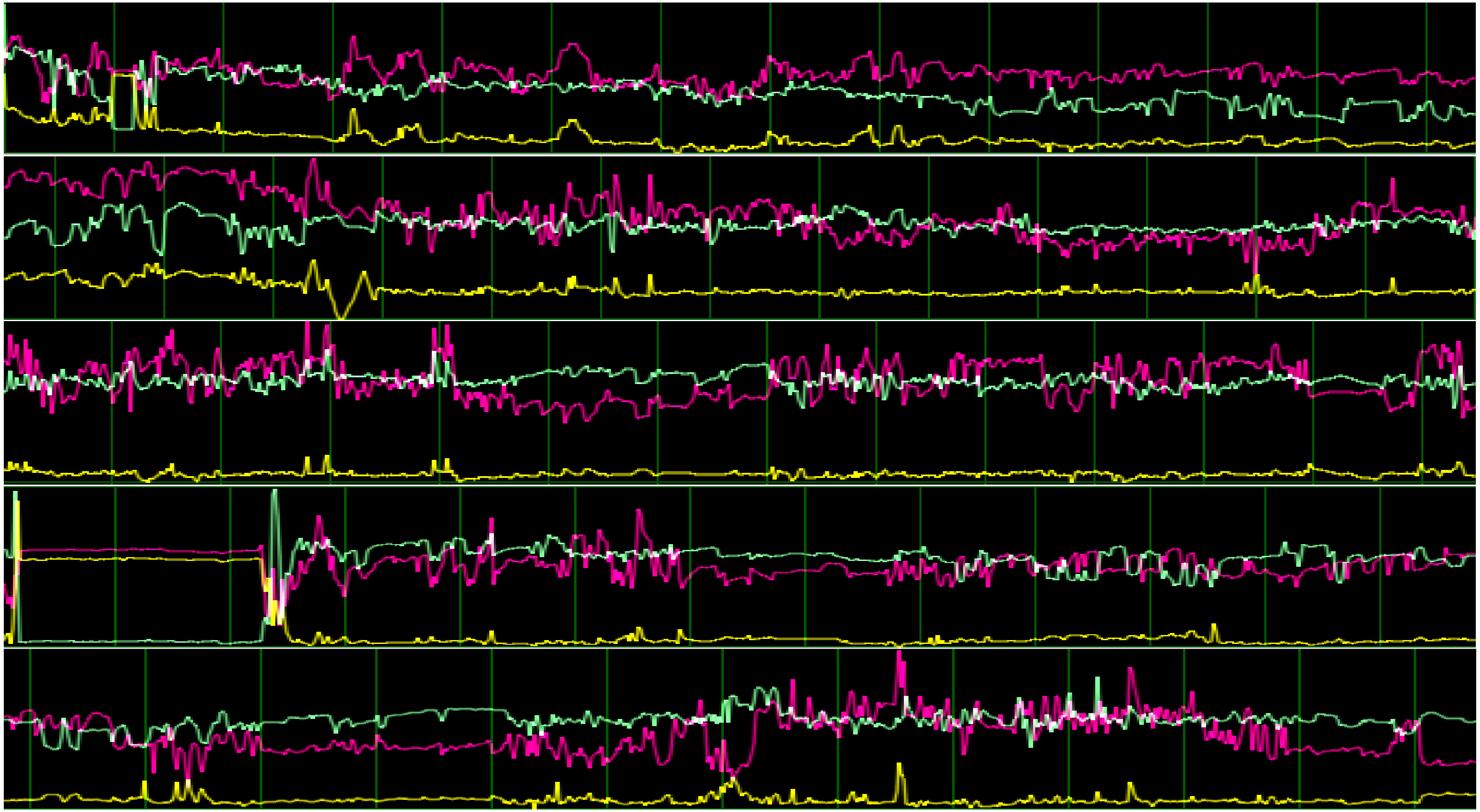
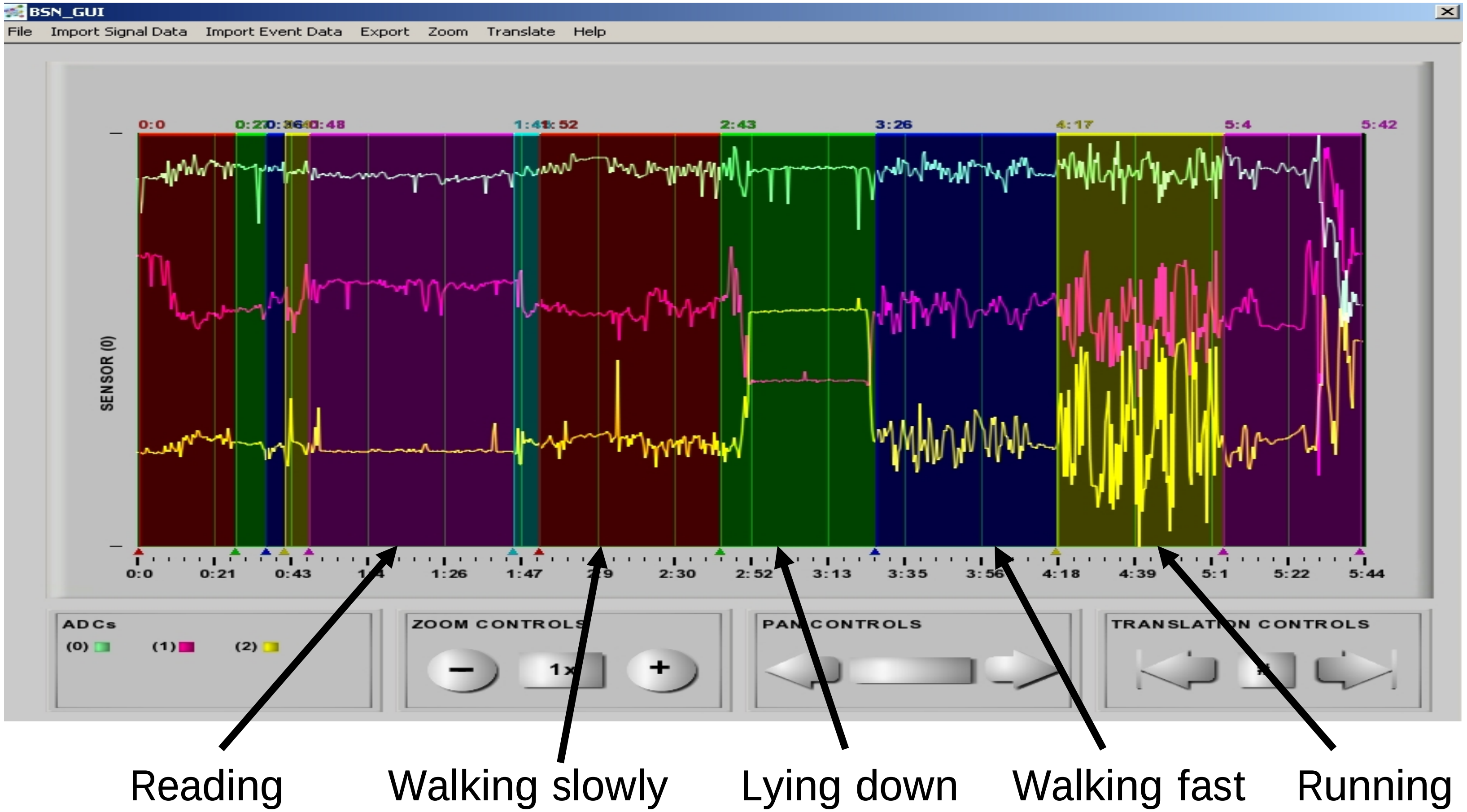
Home Monitoring

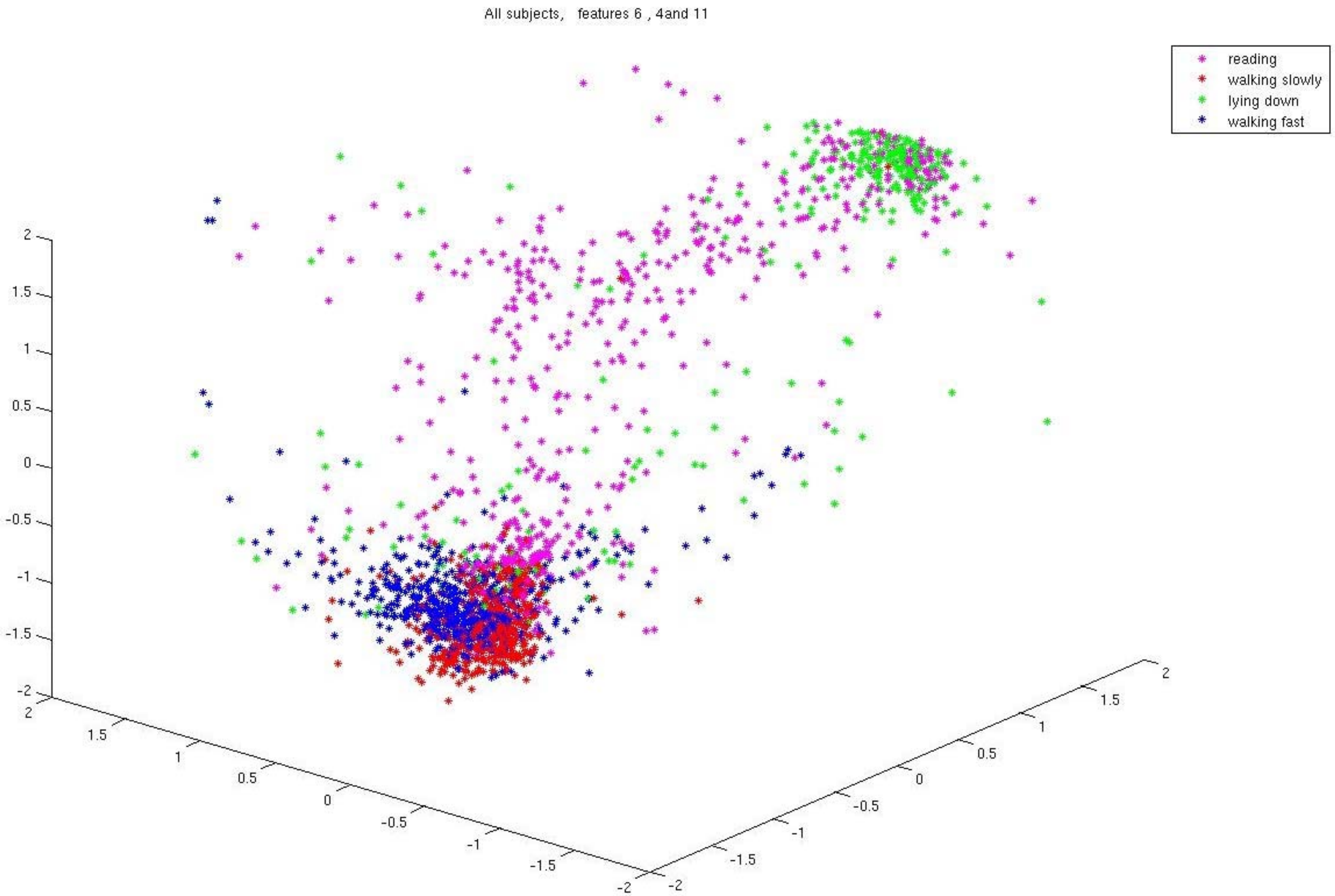
5 Hours of patient's day



Activity Labelling



Activity Classification



Guang-Zhong Yang, Omer Aziz, et al, BSN 2006

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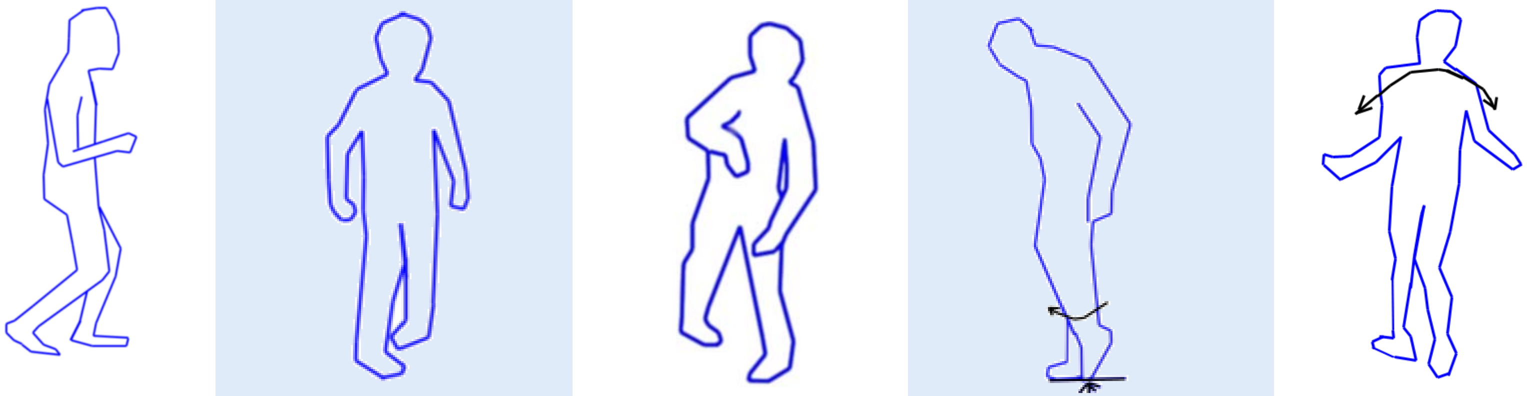
From Gait to Behaviour Profiling

- **Gait abnormalities**



Propulsive gait | Scissors gait | Spastic gait | Steppage gait | Waddling gait

- **Typical associated diseases**

Propulsive gait

- Carbon monoxide poisoning
- Manganese poisoning
- Parkinson's disease
- Temporary effects from drugs

Scissors gait

- Stroke
- Cervical spondylosis with myelopathy
- Liver failure
- Multiple sclerosis
- Pernicious anemia
- Spinal cord trauma
- Cerebral palsy

Spastic gait

- Brain abscess
- Brain tumor
- Stroke
- Head trauma
- Multiple sclerosis

Steppage gait

- Guillain-Barre syndrome
- Herniated lumbar disk
- Multiple sclerosis
- Peroneal muscle atrophy
- Peroneal nerve trauma
- Poliomyelitis
- Polyneuropathy
- Spinal cord trauma

Waddling gait

- Congenital hip dysplasia
- Muscular dystrophy
- Spinal muscle atrophy

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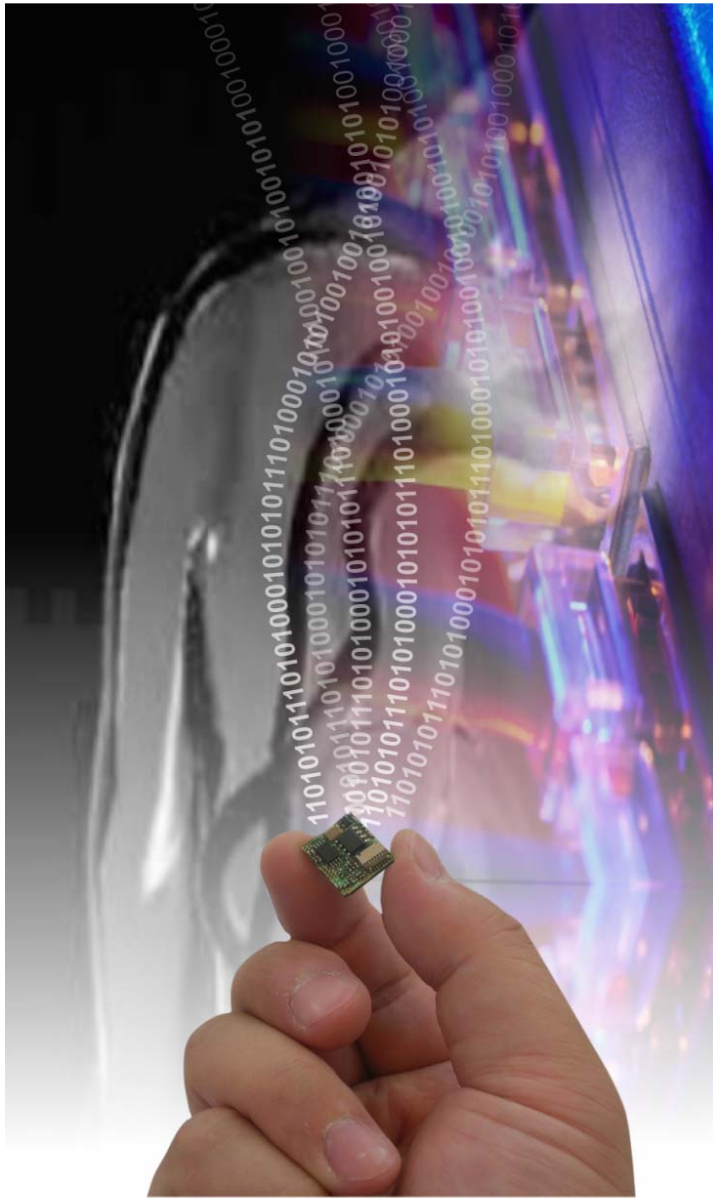

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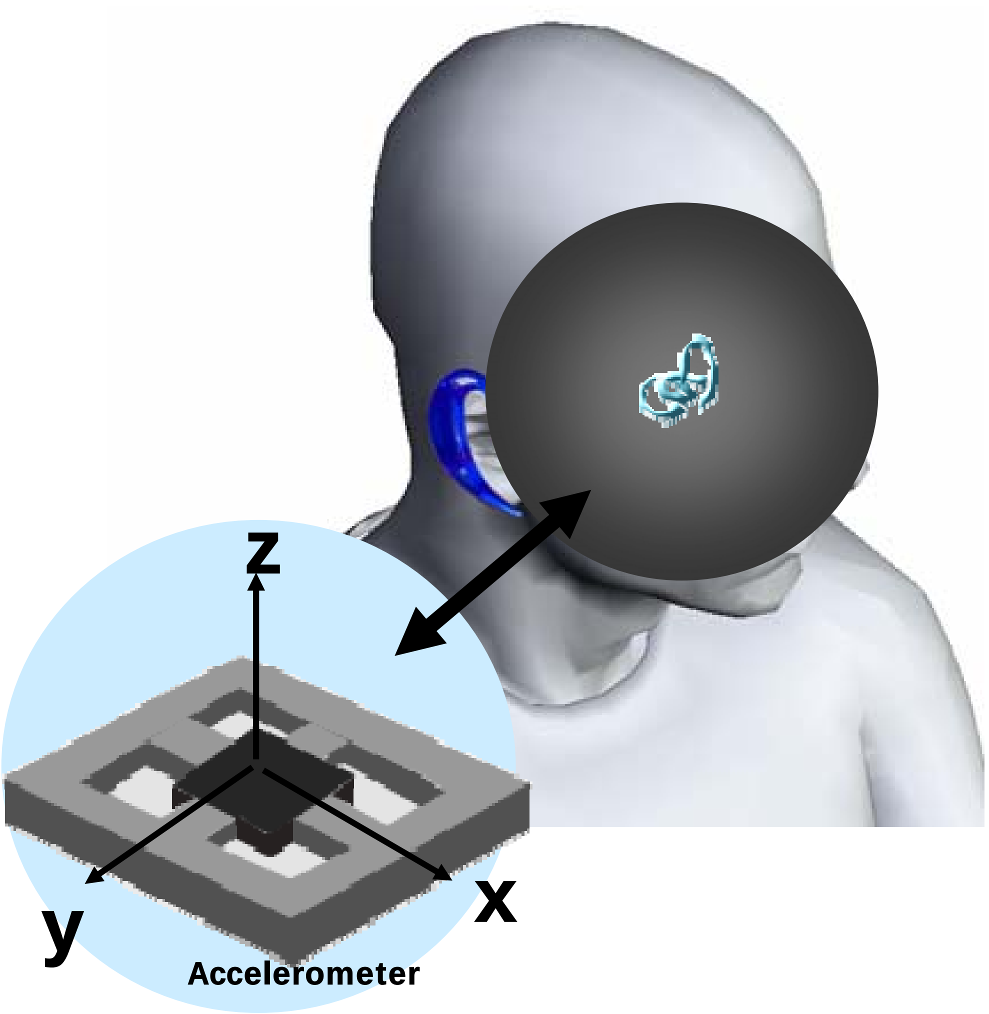
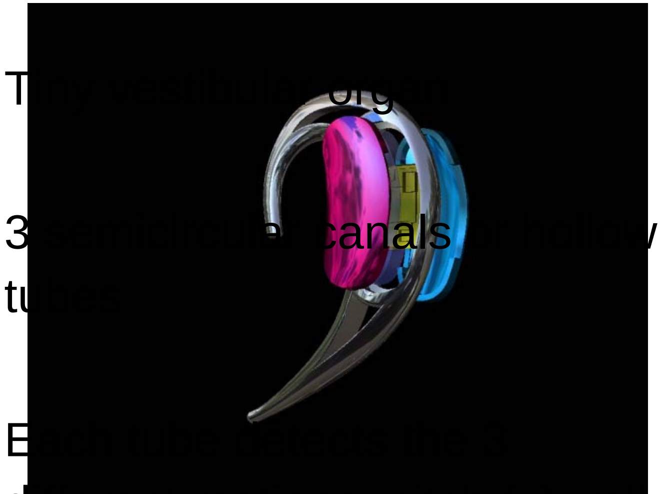
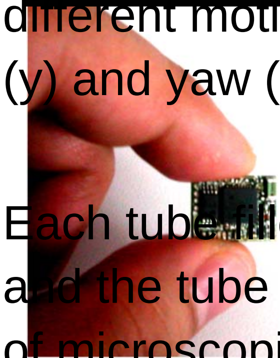
e-AR: How does it works?
Human-inner ear / e-AR Sensor







- T[illegible] org[illegible]
- 3 [illegible] canals [illegible] tu[illegible]
- E[illegible] different motions: pitch (x), roll (y) and yaw (z)
- Each tube filled with liquid, and the tube contains millions of microscopic hairs

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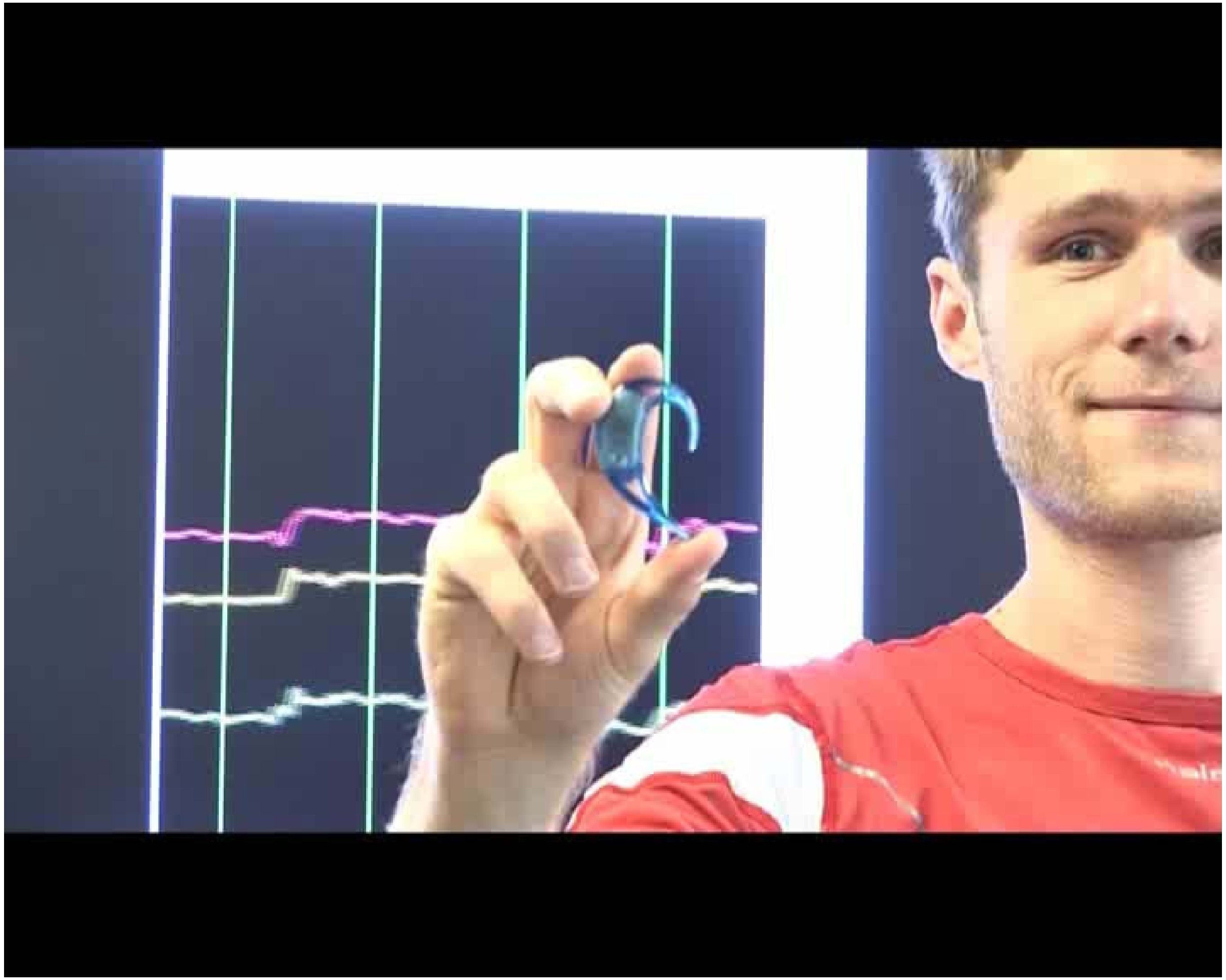

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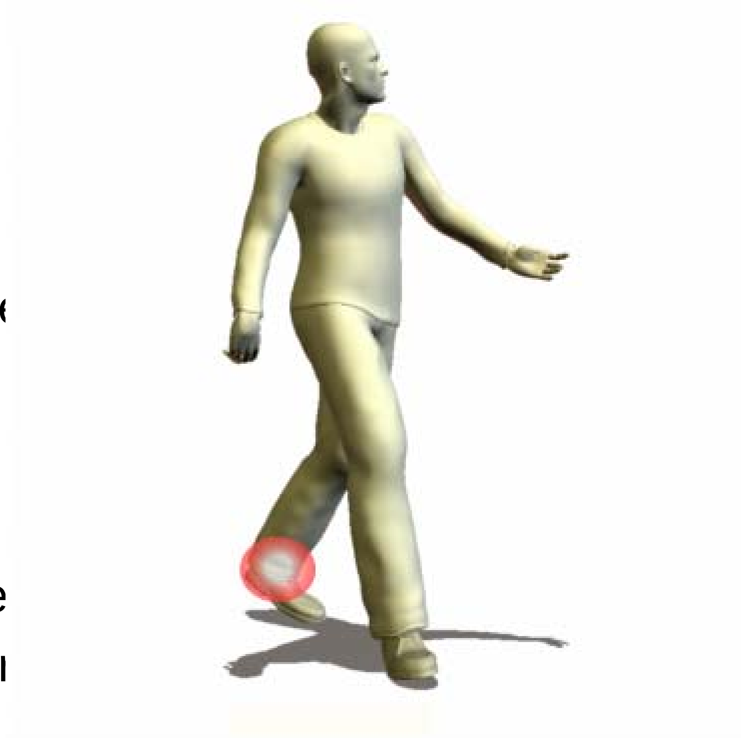
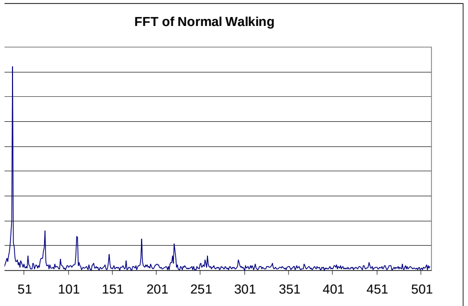
e-AR for Detecting Changes in Gait Due to Injury

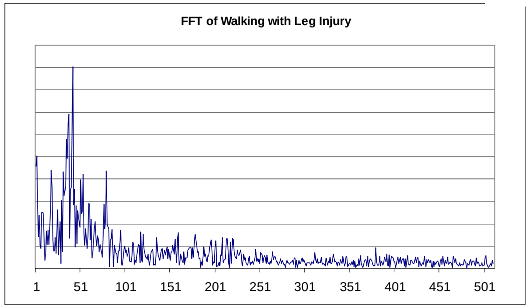
- After the initial experiment, one of the volunteer had an ankle injury
- Accelerometer readings of the subject we recorded before and after the injury, and when the subject is fully recovered
- Distinctive patterns were found when the subject was suffering from the ankle injui



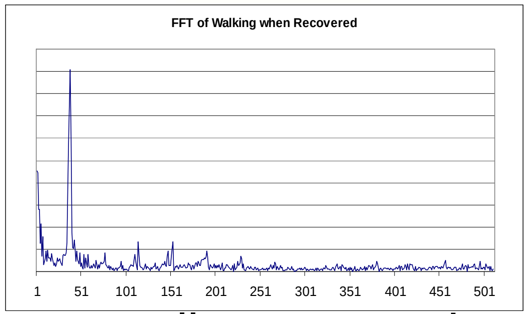
FFT of accelerometer readings



Before Injury



After Injury



Fully Recovered

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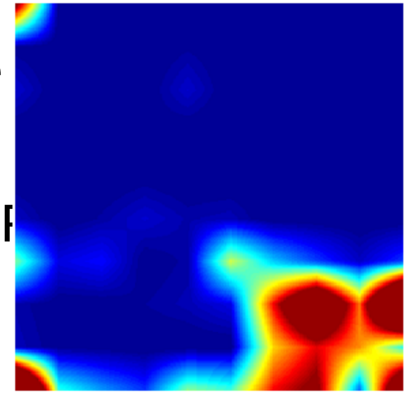
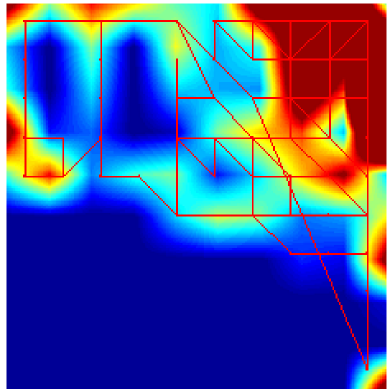
Ankle injury – Cont'd

- STSOM – different clusters are formed for the different gait patterns (using features from FF

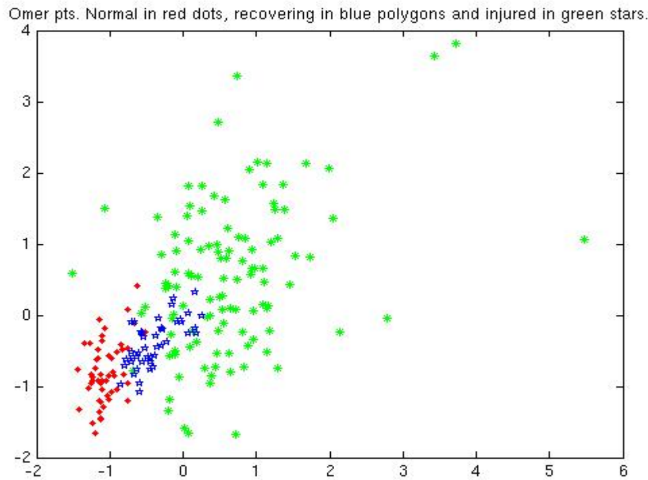


Normal gait



Injured gait

- KNN – clusters are formed for different gaits (using features from wavelet transform), and the recognition accuracy is above 90%



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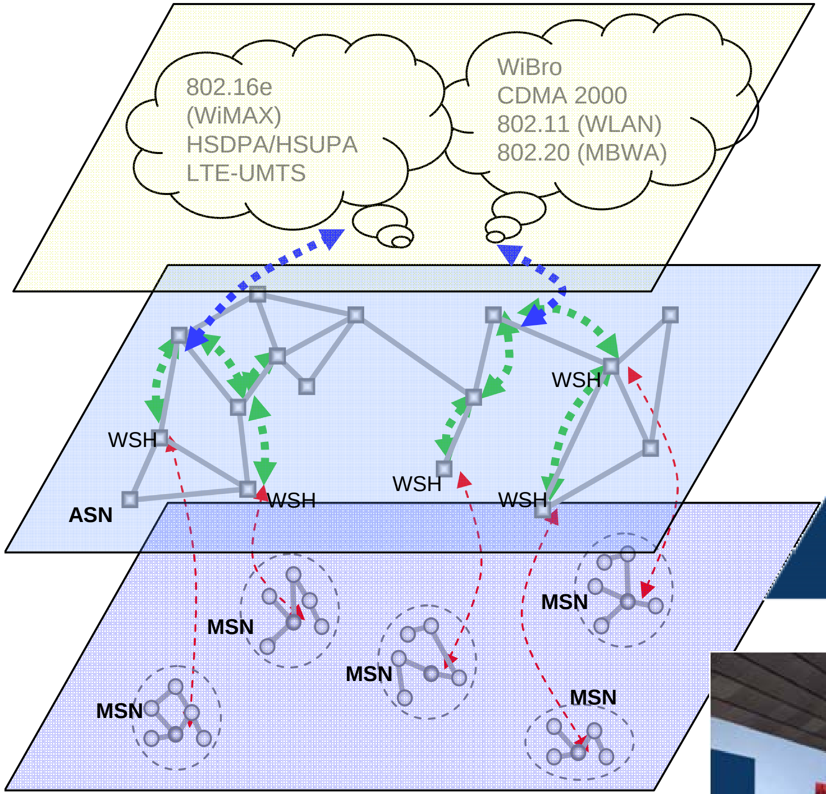
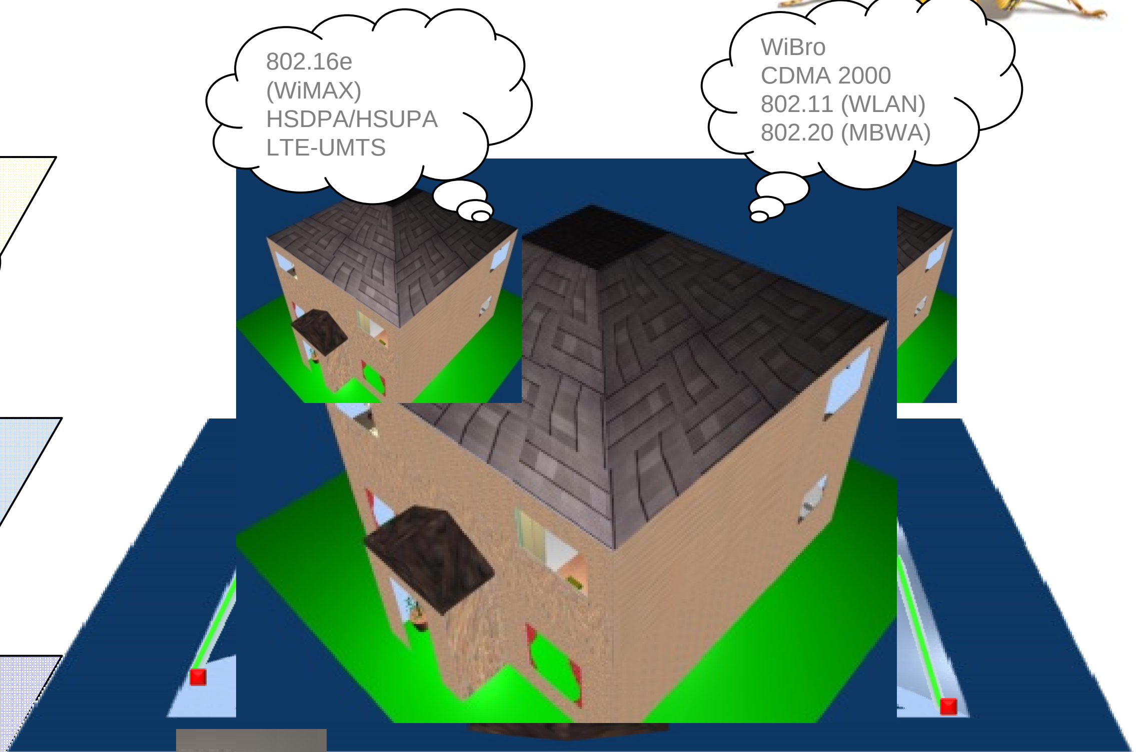
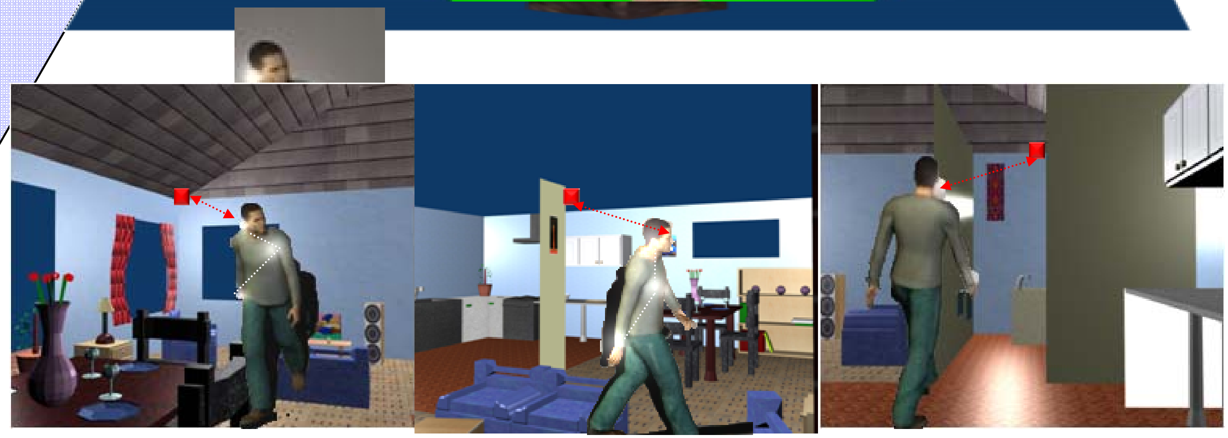
Mapping to Elderly Care

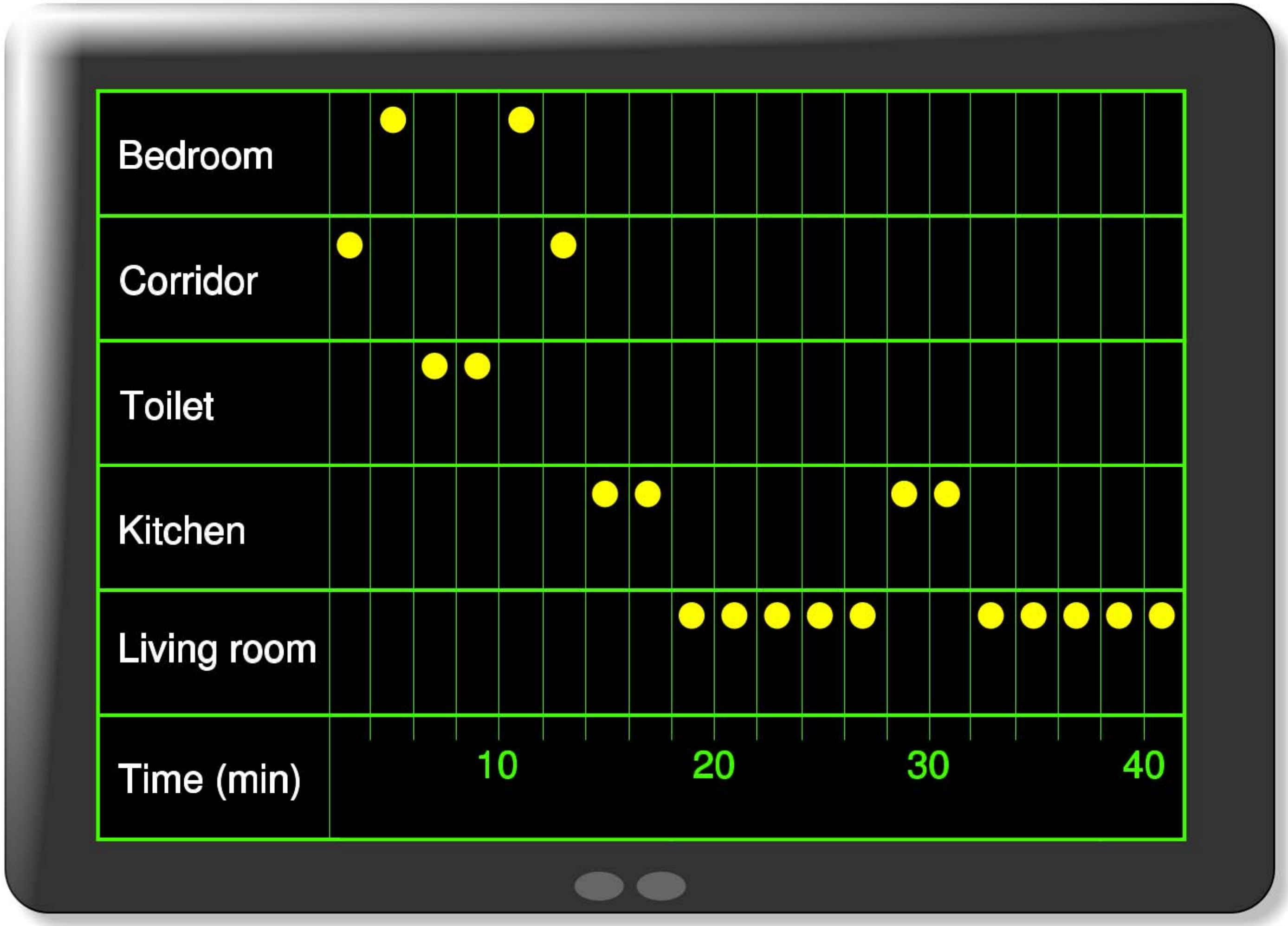
Patient moving between different locations - Patient Discovery



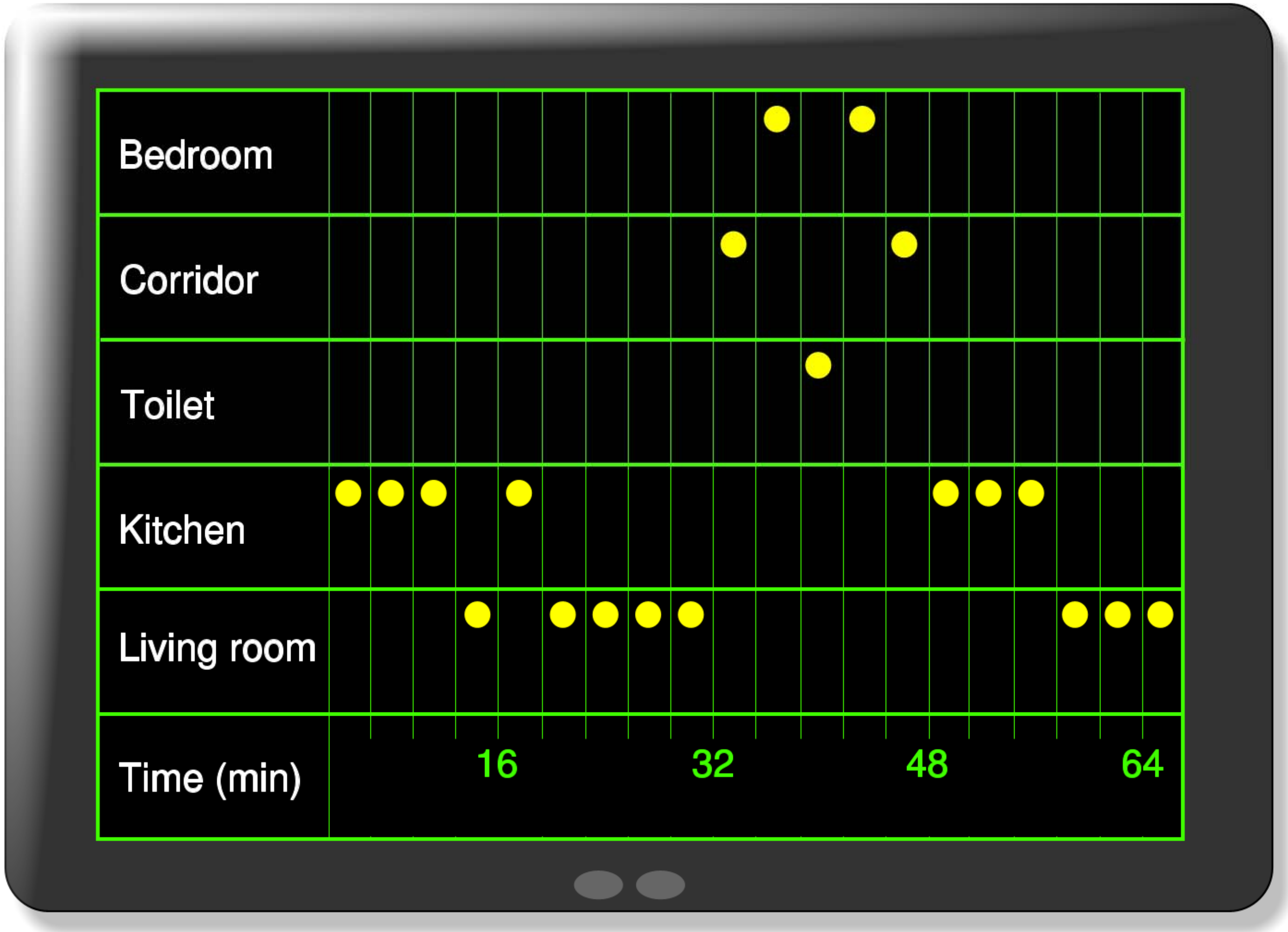




A Question to the Audience ?



A Question to the Audience ?



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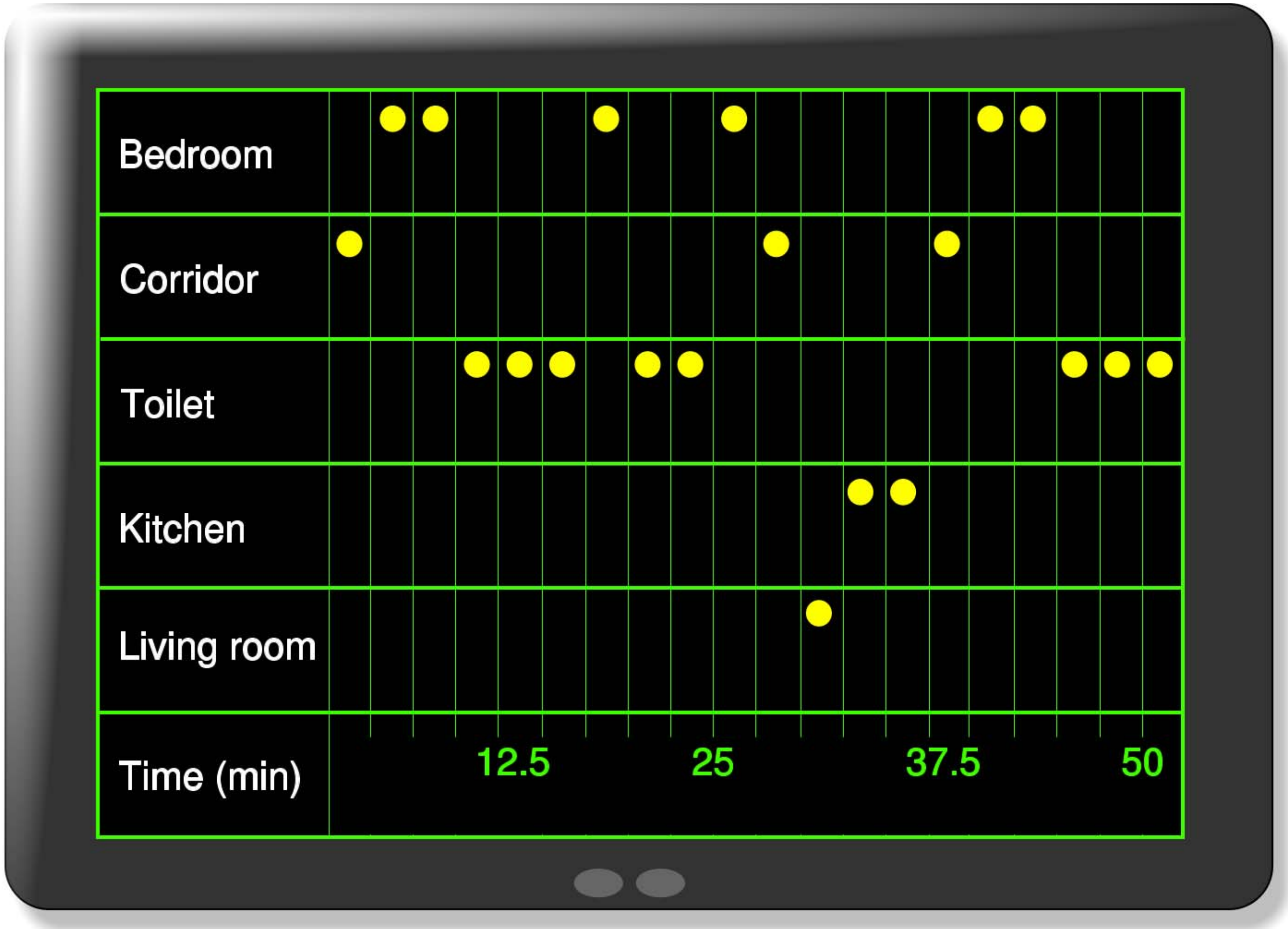
A Question to the Audience ?



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Focus of This Talk

- Technical Challenges and Opportunities of BSN
- Healthcare and Wellbeing Monitoring
- Sports and Entertainment
- Conclusions

Sport Performance Analysis

Applied health science
Wheaton college

Center for Human Performance
San Diego, California

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Lab based Analysis

www.sportsci.com

Gait cycle

Initial contact | Loading response | Mid stance | Terminal stance | Preswing | Initial swing | Mid swing | Terminal swing

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Running gait

Initial contact

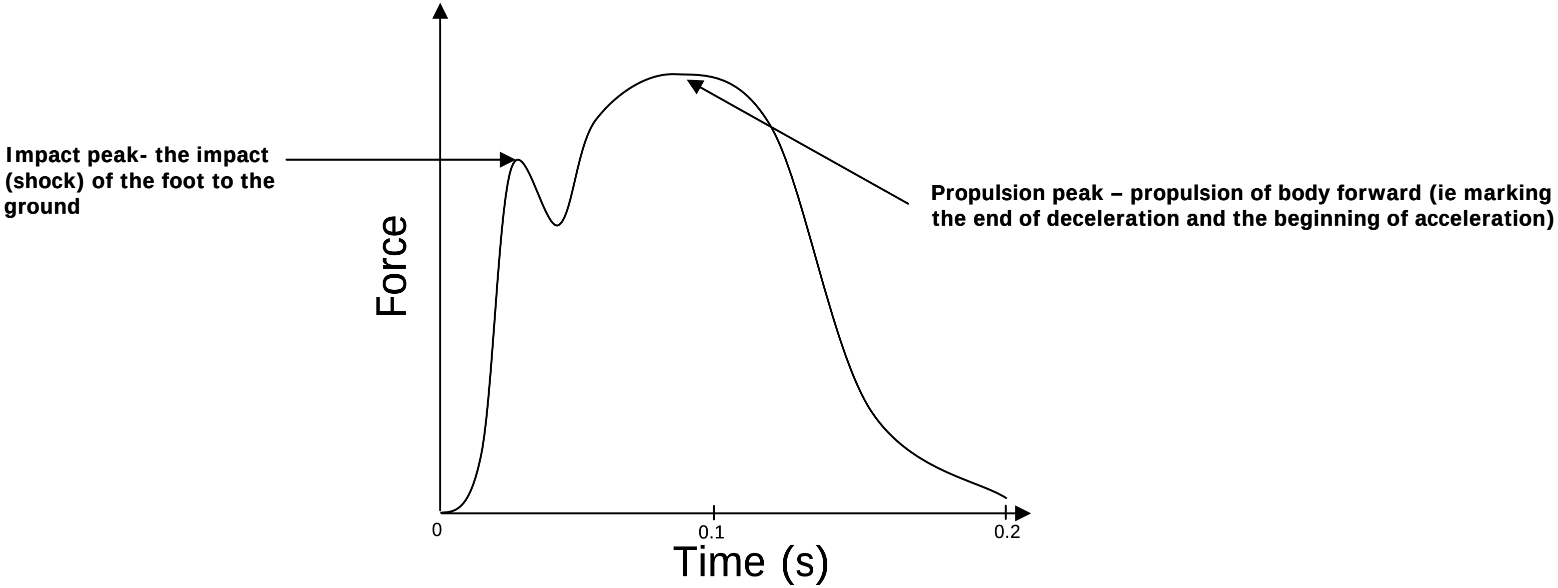
Stance phase reversal

Toe off

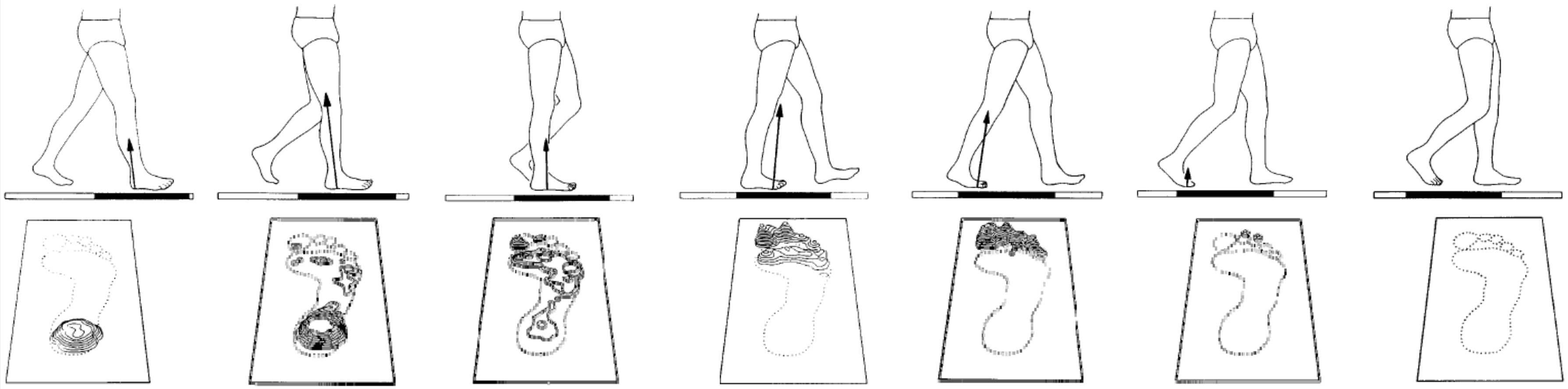
Swing phase reverse

Initial contact

Ground reaction force



T.F. Novacheck, "The Biomechanics of running", Gait and Posture 7 (1998) 77-95



C. Vaughan *et. al*, "Dynamics of Human Gait" (2nd ed), Kiboho Publishers, Cape Town South Africa, 1999

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Sprinting posture

- Starting
  - Stay forward (head down)
- Acceleration (10-30m)
  - foot touches down in front of centre of gravity
  - Forward body lean begins to decrease until normal sprinting position is reached
- Maximum speed (30-60m)
  - Push off angle from ground ~50-55^{o}
  - Trunk erect with ~5^{o} forward lean
  - Foot meets ground with ankle slightly extended directly under centre of gravity

Speed Endurance (60m onwards)

Finishing

- Increase stride frequency

http://www.sport-fitness-advisor.com/sprintingtechnique.html

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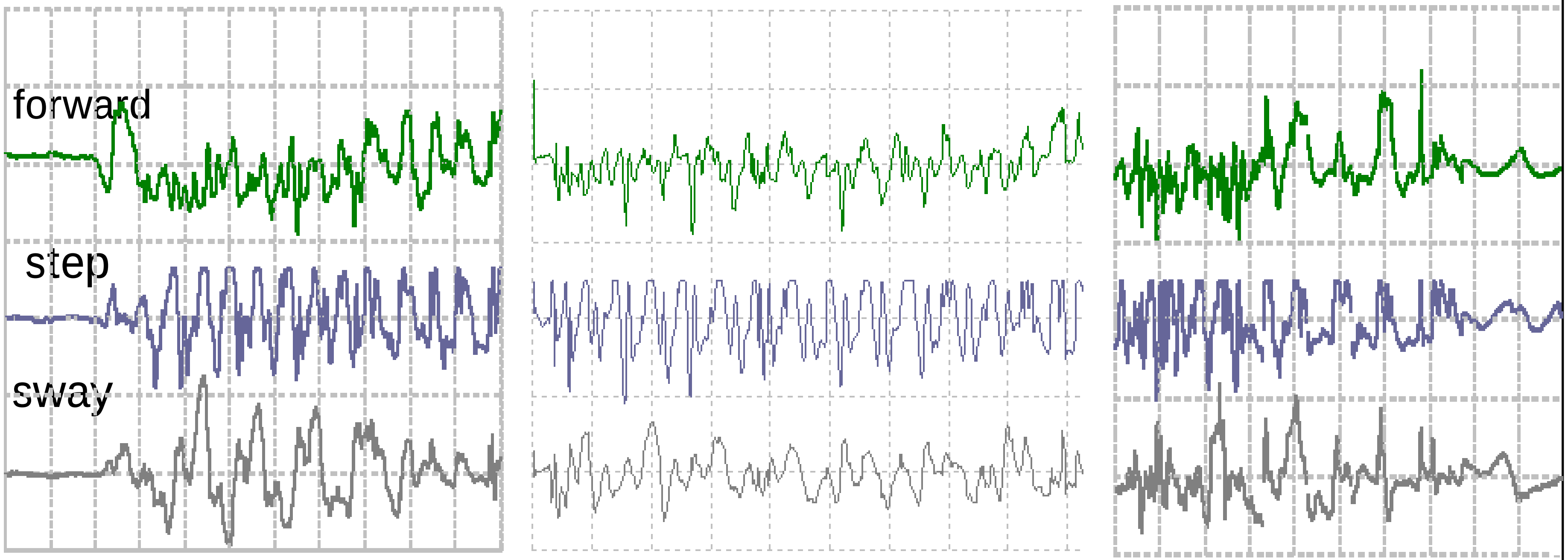
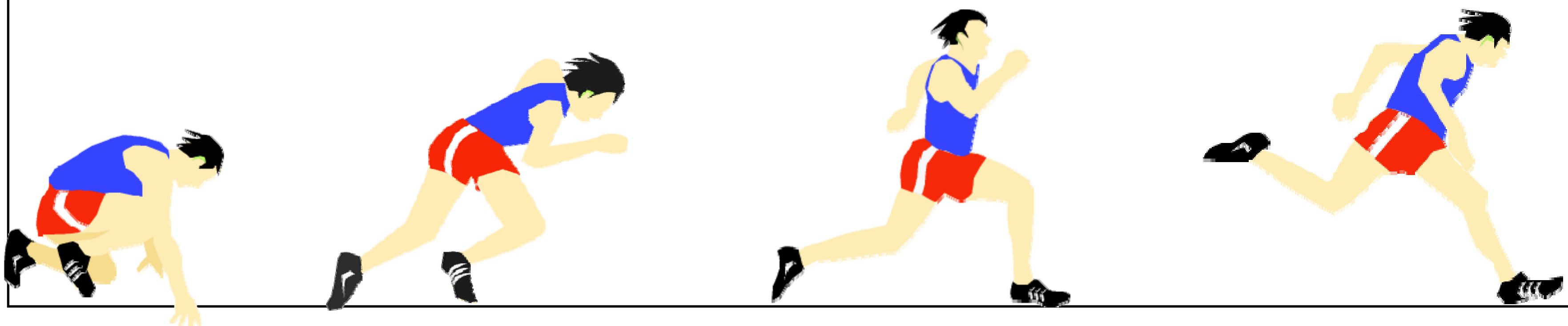
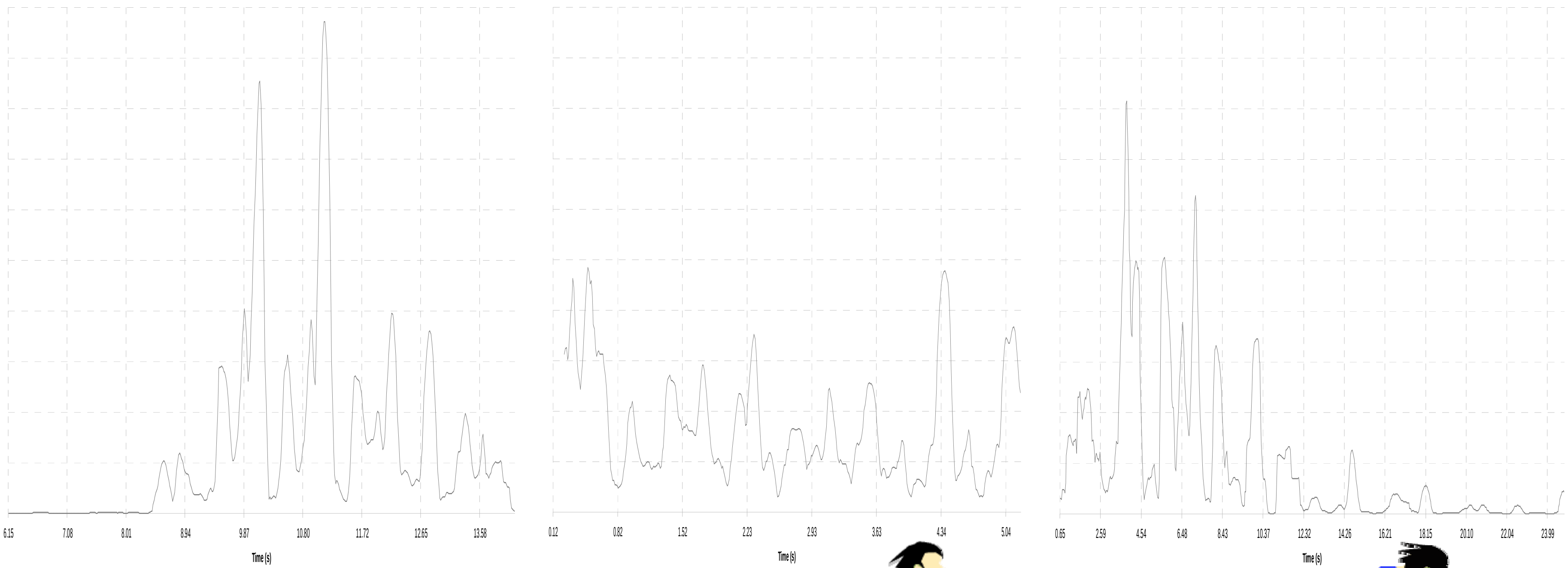
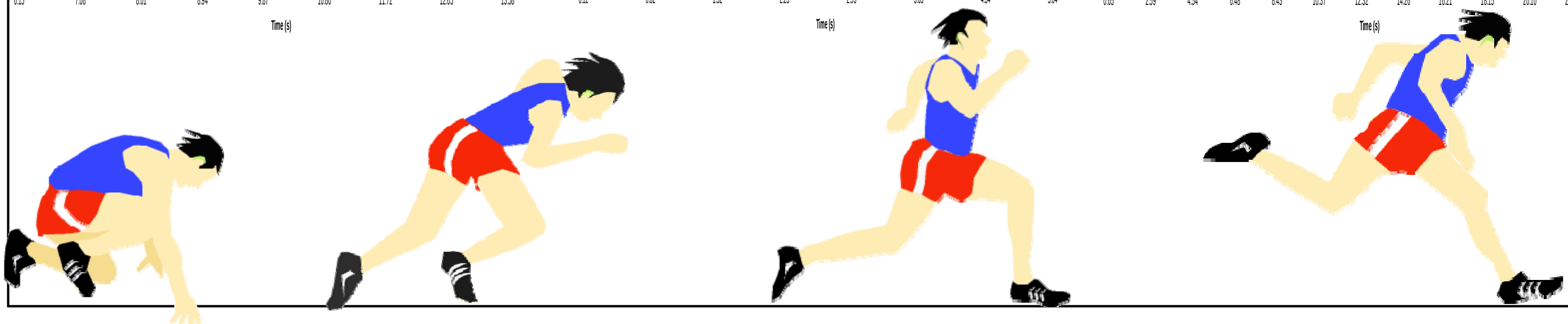
Sprinting



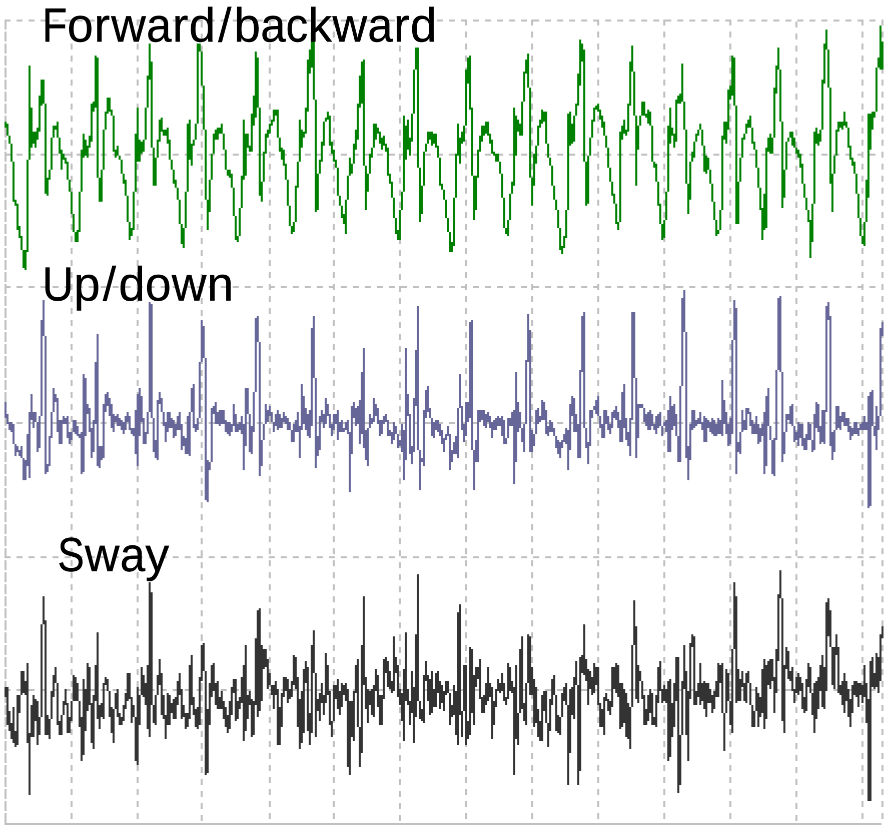


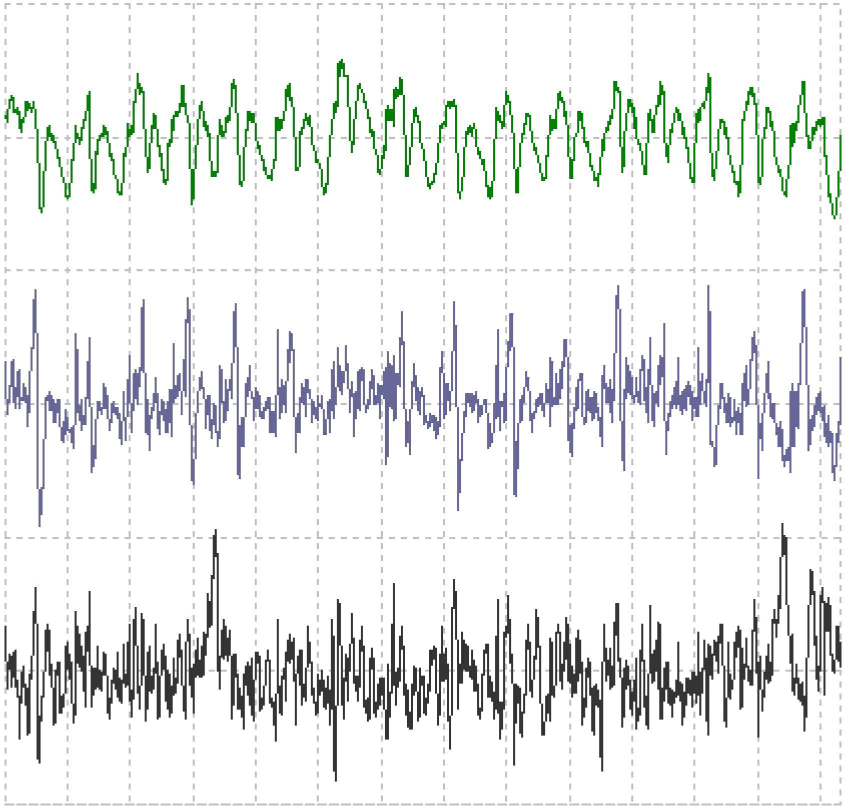
Sprinting - Swaying



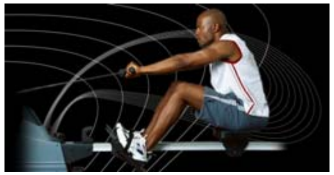


Rowing with e-AR

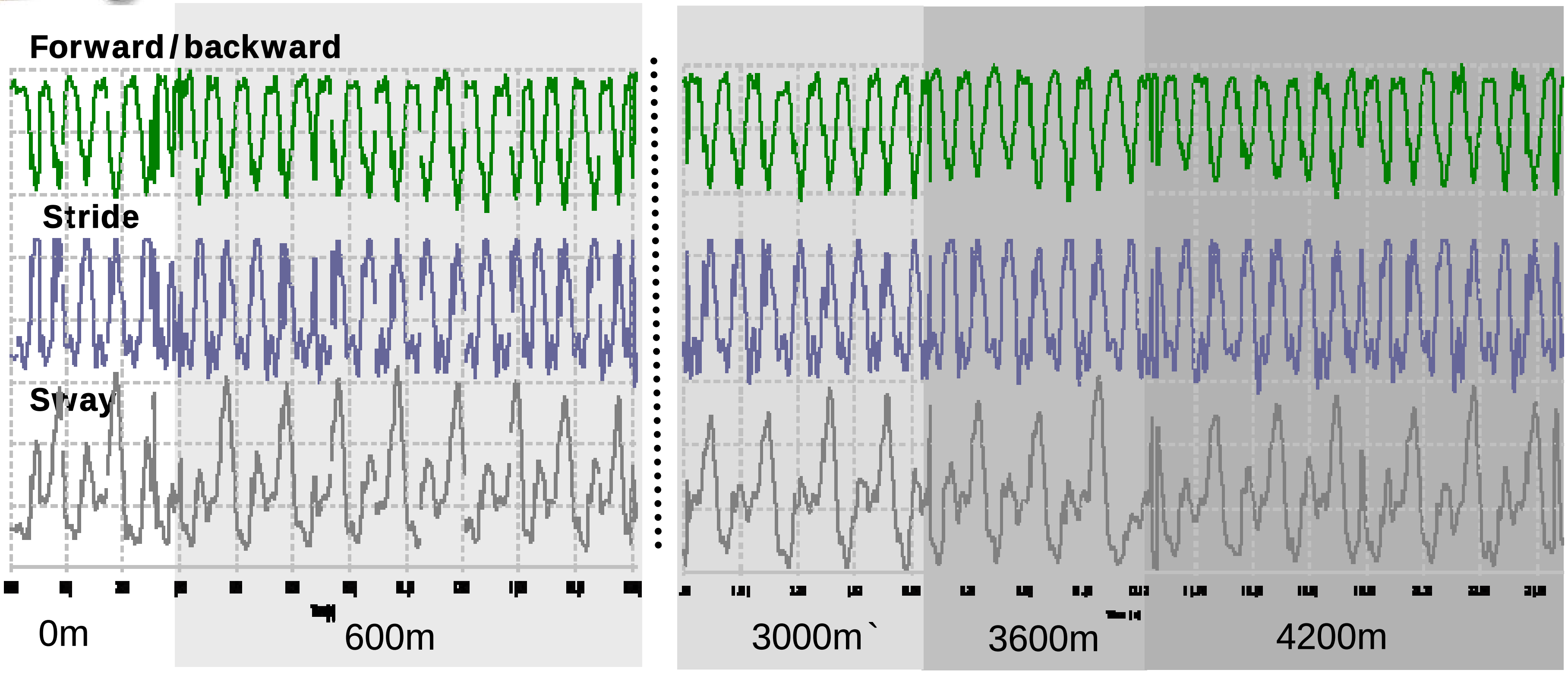


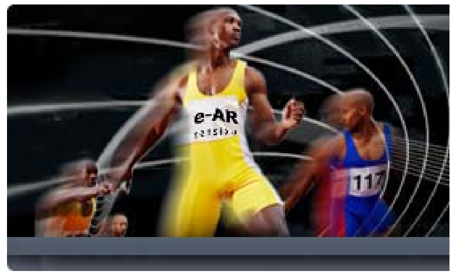


Steady speed **Slowing down**

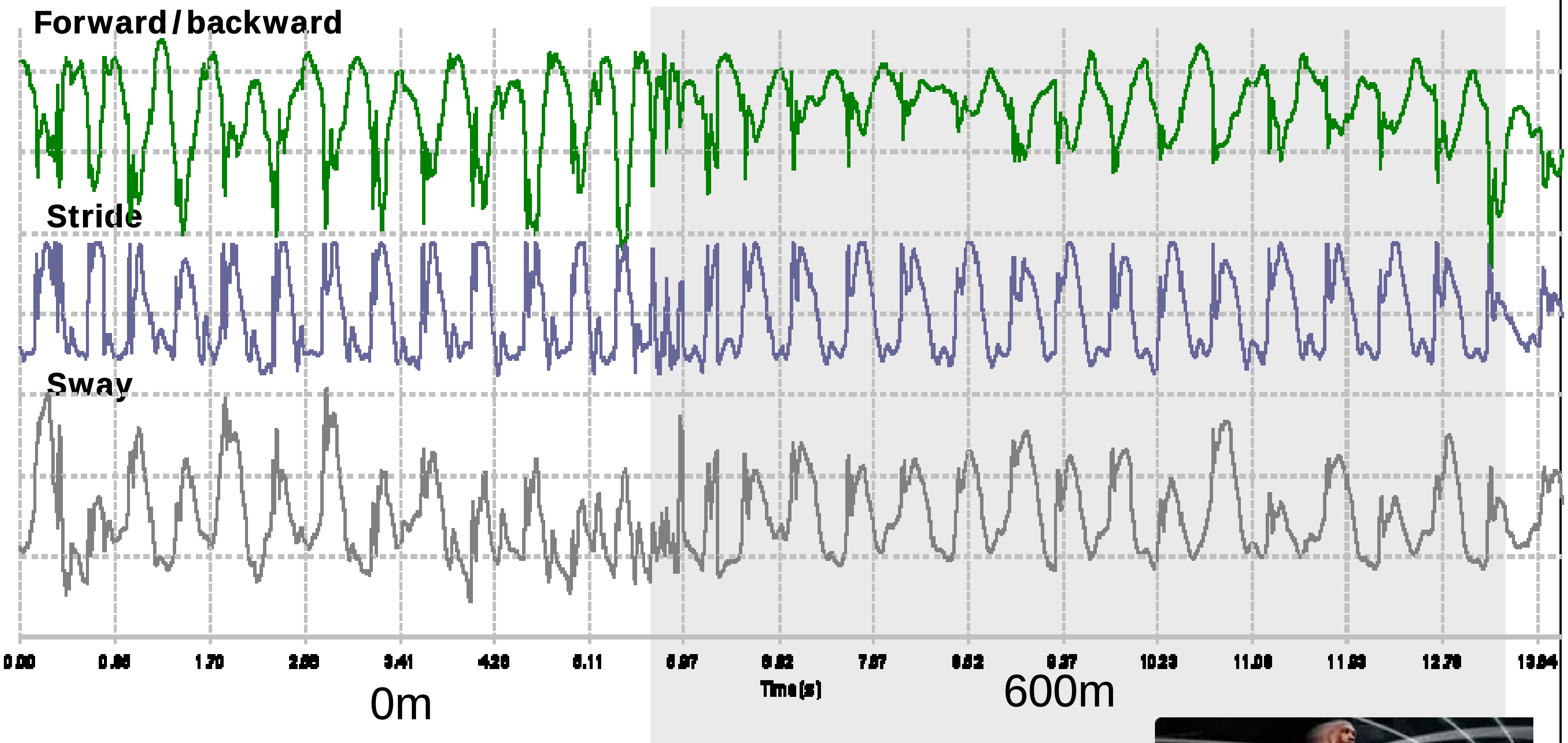


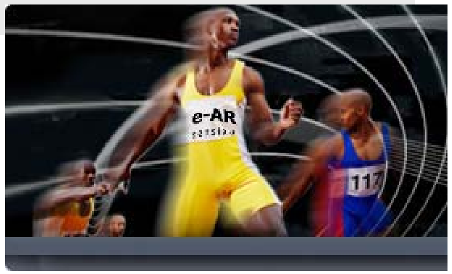
Distance running





Distance running





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Safety and Security

Equipment rental

Tracking

Performance analysis

Passes & Tickets

Social Interactions

Access Control

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Safety and security

Performance analysis

Tracking

Passes & Tickets

Social Interactions

Access Control

Conclusions

- The boundary between healthcare and general wellbeing monitoring is increasingly blurred, body sensor networks provide a unique platform for the development of pervasive healthcare, well being and physically engaged gaming

- Hardware miniaturisation, ultra-low power design and autonomic (cognitive) sensing

- Pervasive, user centric design is key to different application scenarios

- Heterogenic integration and muti-sensor integration/fusion with ambient sensing is essential

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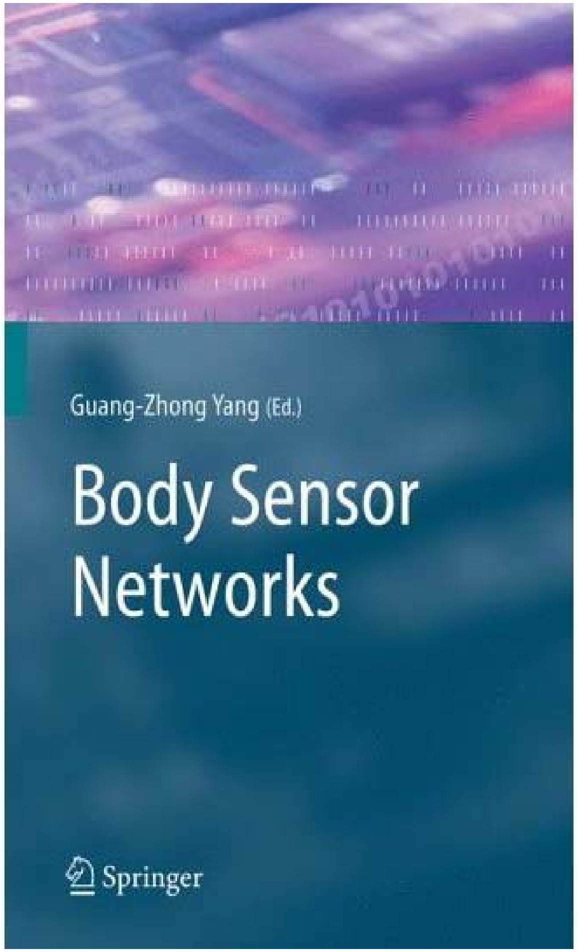
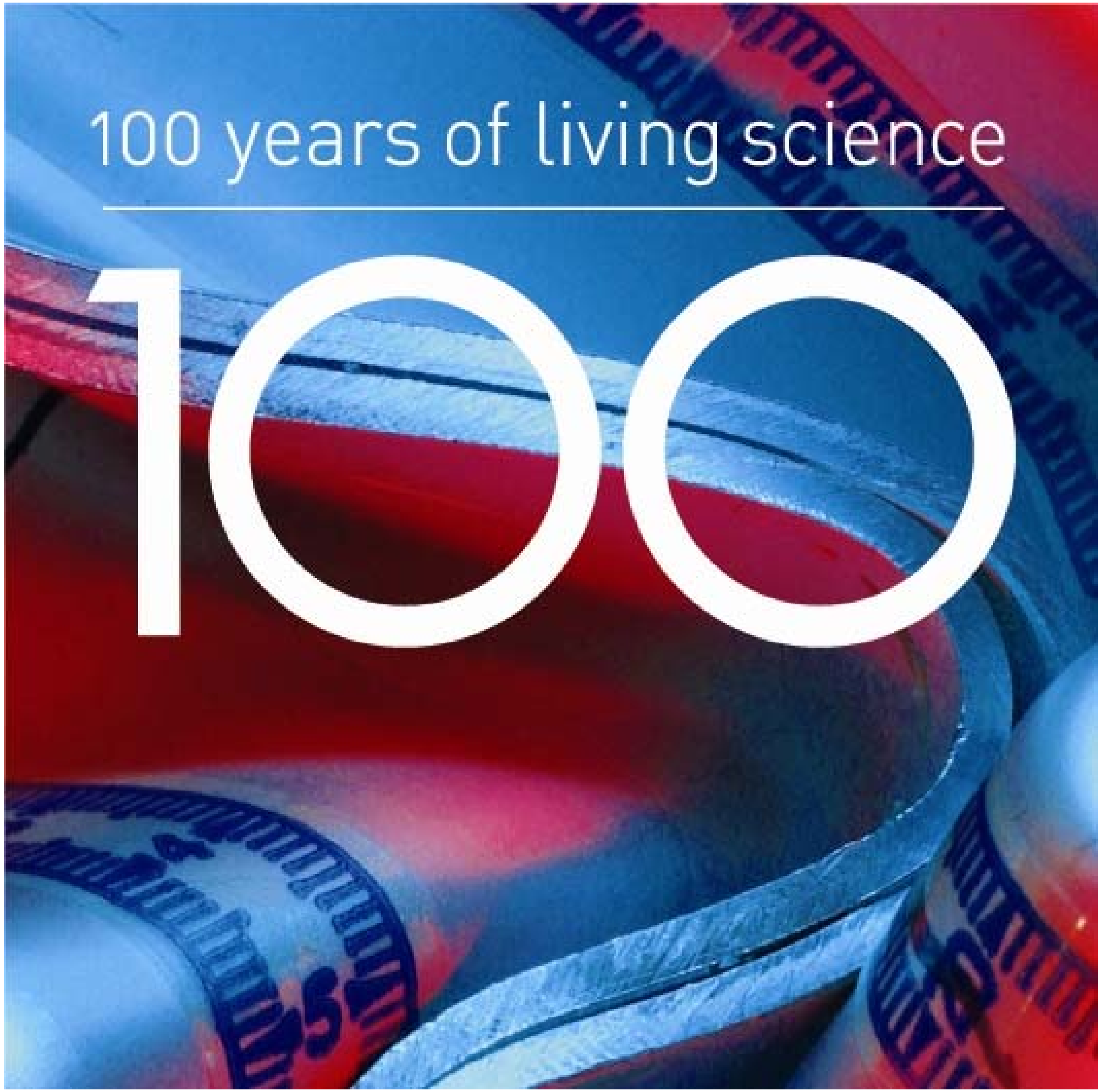
To Probe Further: http://ww.bsn-web.org




100 years of living science
100