Dynamic CT for MSK applications

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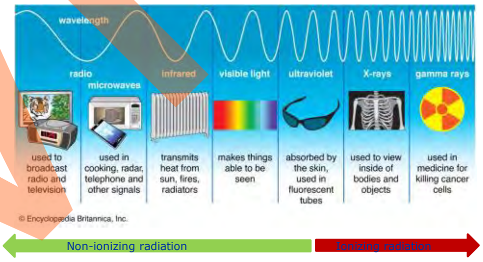
WHAT ARE MEDICAL IMAGES ?

Medical images represent a collective name for images generated by the various techniques to visualize the internal structures of the body.

They play a vital role in modern medicine for providing diagnoses, detecting and monitoring diseases as well as supporting medical interventions

CONCEPT OF MEDICAL IMAGING

ELECTROMAGNETIC SPECTRUM



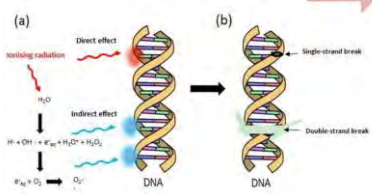
CONCEPT OF MEDICAL IMAGING

MEDICAL IMAGING DEVICES

CONCEPT OF MEDICAL IMAGING

IONIZING RADIATION

Ionizing radiations have enough energy to remove electrons from atoms and molecules



CONCEPT OF MEDICAL IMAGING

IONIZING RADIATION

Ionizing radiation can penetrate living tissue and damage cells in this tissue through the production of positively charged atoms (ions). Exposure to ionizing radiation can increase the risk of developing cancer. Ionizing radiation can also lead to direct damage to tissue, such as redness of the skin after radiotherapy.

The risk of adverse effects due to ionizing radiation is cumulative. This means that the risk of adverse effects increases the more irradiation one receives.

https://www.zuinigmetstraling.be/nl

CONCEPT OF MEDICAL IMAGING

NATURAL BACKGROUND RADIATION

Natural background radiation

The main sources of natural background radiation are:

- radiation from space (cosmic rays)
- decay of radioactive elements in the Earth's crust (particularly radon)
- building materials in houses
- our own body

The background radiation we receive is not the same everywhere. In some places there are more radioactive elements in the soil than in other places. There is also more background radiation at high altitudes because we are exposed to more cosmic radiation due to the thinner atmosphere.

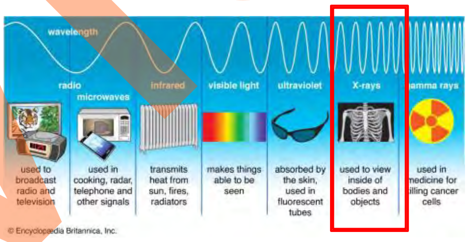
https://www.zuinigmetstraling.be/nl

Within medical imaging, 6 imaging techniques use ionizing rad

- radiography
- radioscopy
- CT-scan
- planar scintigraphy
- Single-Photon Emission Computed Tomography (SPEC
- Positron Emission Tomography (PET)

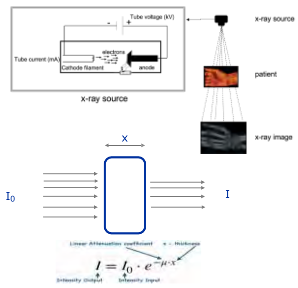
Bron van bestraling	Dosis in millisievert	Duur van de natuurlijke blootstelling om deze stralingsdosis te bereiken
Natuurlijke blootstelling in België	2,4 mSv	1 jaar
4 uur in een passagiersvliegtuig (vanwege de grotere hoogte en de dunnere atmosfeer)	0,005 mSv	1 dag
7 dagen skiën in de bergen	0,005 mSv	1 dag
Radiografie van de lage rug (volledig onderzoek)	1,8 mSv	9 maanden
Radiografie van de buik	0,5 mSv	3 maanden
Radiografie van het bekken	0,5 mSv	3 maanden
Mammografie	0,3 mSv	1,5 maanden
Radiografie van de longen (zijaanzicht)	0,06 mSv	9 dagen
Radiografie van de longen (vooraanzicht)	0,04 mSv	6 dagen
Coronaire CT-angiografie (CT van het hart)	10,5 mSv	4,5 jaar
CT van de lage rug	7 mSv	3 jaar
CT van de buik	7 mSv	3 jaar
CT van de thorax	3 mSv	15 maanden
CT van het hoofd	1,5 mSv	8 maanden
CT van de sinussen	0,1 mSv	15 dagen
Onderzoek doorbloeding van het hart (stress en rust)	12 mSv	5 jaar
Onderzoek doorbloeding hersenen	6 mSv	2,5 jaar
PET onderzoek	4,5 mSv	2 jaar
Onderzoek skelet	4 mSv	20 maanden
Onderzoek doorbloeding longen	2 mSv	10 maanden
Onderzoek schildklier	1 tot 2 mSv	5 tot 10 maanden
Onderzoek van de nieren	1 tot 1,5 mSv	5 tot 8 maanden
Onderzoek naar maagreflux	1 mSv	5 maanden
Conebeam CT	0,2 mSv	1 maand
Radiografie van een volledige kaak (orthopantogram/panoramische opname)	0,01 mSv	2 dagen
Gewone radiografie van de tanden	0,005 mSv	1 dag

https://www.zuinigmetstraling.be/nl



CONCEPT OF MEDICAL IMAGING

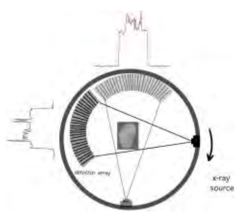
X-RAY IMAGING



$$I = I_0 \cdot e^{-\mu \cdot x}$$

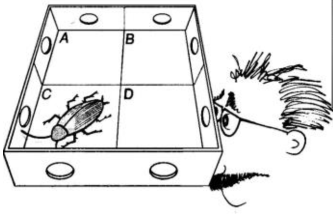
CONCEPT OF MEDICAL IMAGING

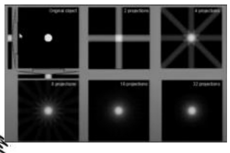
X-RAY IMAGING



CONCEPT OF MEDICAL IMAGING

CT IMAGING

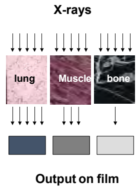


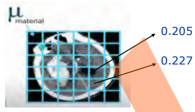


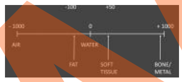
Hounsfield unit

ATTENUATION OF X-RAYS

- X-ray attenuation is determined by different factors:
  - Energy of incoming beam ($1/E^3$)
  - Atomic number of object (Z^3)
  - Density of object
  - Size of object (l)
- Effective atomic number
  - Soft tissue Z=7.5
  - Bone Z = 11



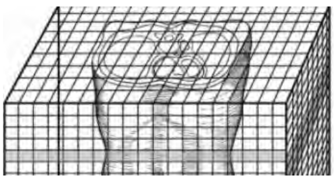


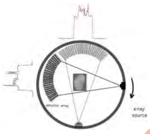


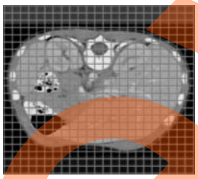
Hounsfield unit

CONCEPT OF MEDICAL IMAGING

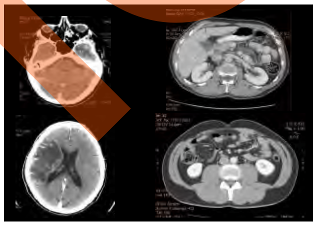
CT IMAGING







CT-IMAGES



A CT image is a pixel-by-pixel map of X-ray beam attenuation (essentially density) in Hounsfield Units (HU)

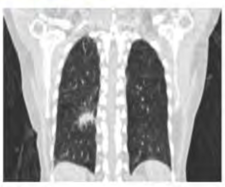
Bright = "hyperattenuating" or "hyperdense"

MEDICAL IMAGES

Usually 2D slices or projections, 3D Volumes

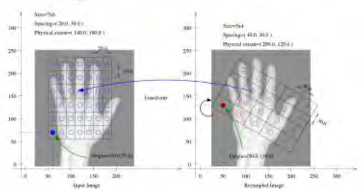
- With pixels or voxel elements

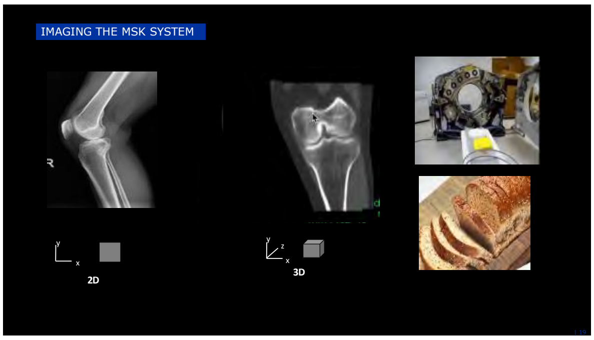
But also 2D+T and 3D+T dynamic sequences, etc

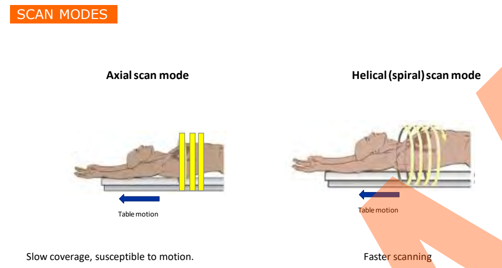


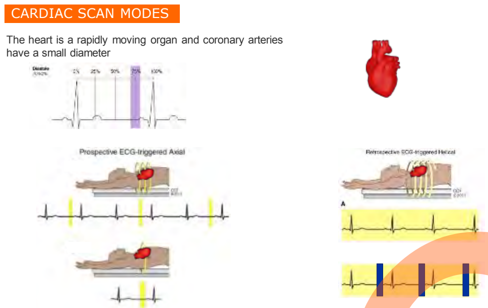
COMMON OPERATIONS ON IMAGES

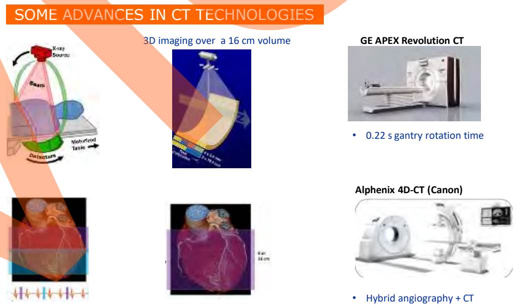
- **Image resampling**
  - Change size, spacing, origin, orientation of an image

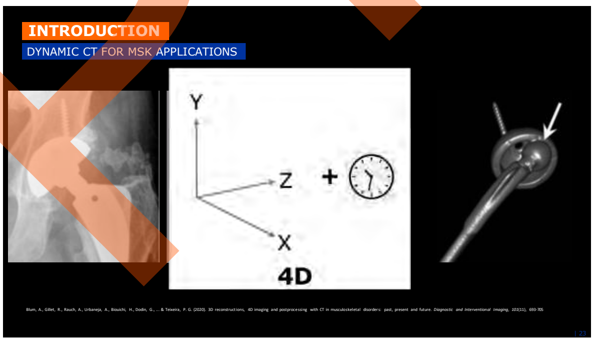


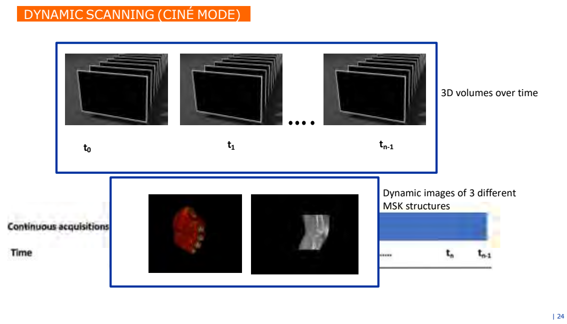

IMAGING THE MSK SYSTEM
2D
3D


SCAN MODES
Axial scan mode
Helical (spiral) scan mode
Table motion
Table motion
Slow coverage, susceptible to motion.
Faster scanning


CARDIAC SCAN MODES
The heart is a rapidly moving organ and coronary arteries have a small diameter
Prospective ECG-triggered Axial
Retrospective ECG-triggered Helical


SOME ADVANCES IN CT TECHNOLOGIES
3D imaging over a 16 cm volume
GE APEX Revolution CT
• 0.22 s gantry rotation time
Alphenix 4D-CT (Canon)
• Hybrid angiography + CT


INTRODUCTION
DYNAMIC CT FOR MSK APPLICATIONS
Y
Z
X
4D


DYNAMIC SCANNING (CINÉ MODE)
3D volumes over time
t_0
t_1
t_{n-1}
Dynamic images of 3 different MSK structures
Continuous acquisitions
Time
t_n
t_{n-1}
| 24


DYNAMIC SCANNING (CINÉ MODE)
4D CT of the lungs
4D CT of the heart
Motion amplitude
4D-CT
4D-PET

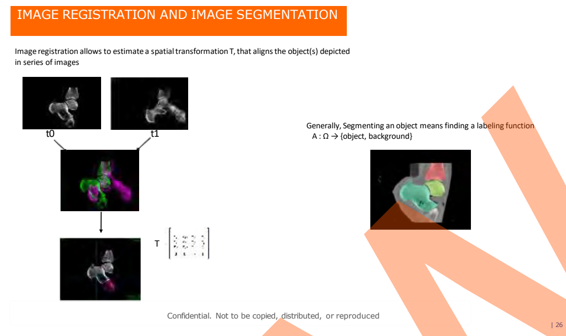


IMAGE REGISTRATION AND IMAGE SEGMENTATION
Image registration allows to estimate a spatial transformation T, that aligns the object(s) depicted in series of images
t0
t1
T
Generally, Segmenting an object means finding a labeling function
A : Ω → {object, background}
Confidential. Not to be copied, distributed, or reproduced
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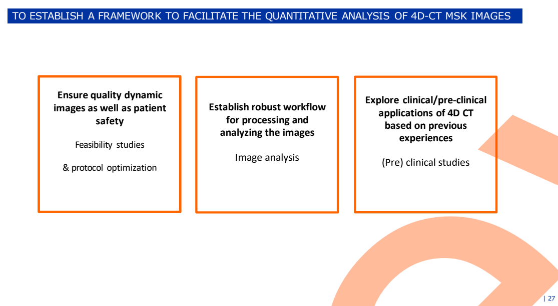
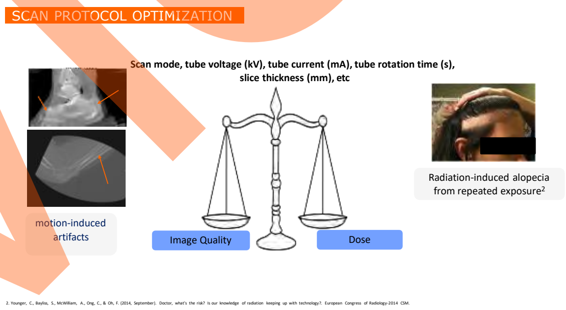
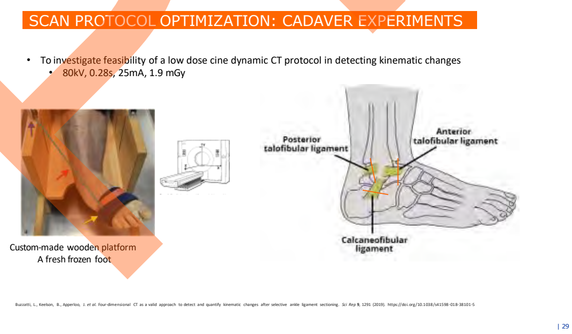
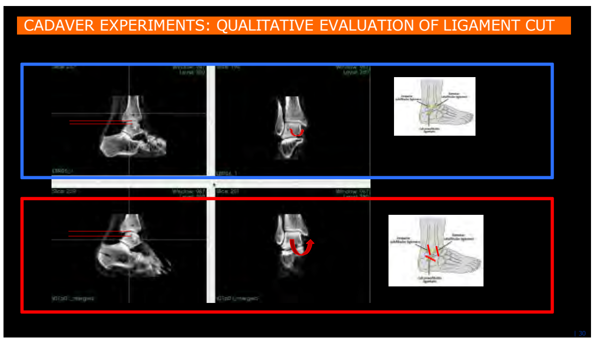

TO ESTABLISH A FRAMEWORK TO FACILITATE THE QUANTITATIVE ANALYSIS OF 4D-CT MSK IMAGES
Ensure quality dynamic images as well as patient safety
Feasibility studies
& protocol optimization
Establish robust workflow for processing and analyzing the images
Image analysis
Explore clinical/pre-clinical applications of 4D CT based on previous experiences
(Pre) clinical studies
| 27

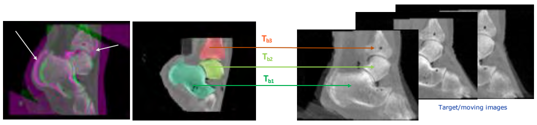

SCAN PROTOCOL OPTIMIZATION
Scan mode, tube voltage (kV), tube current (mA), tube rotation time (s), slice thickness (mm), etc
motion-induced artifacts
Image Quality
Dose
Radiation-induced alopecia from repeated exposure2


SCAN PROTOCOL OPTIMIZATION: CADAVER EXPERIMENTS
To investigate feasibility of a low dose cine dynamic CT protocol in detecting kinematic changes
80kV, 0.28s, 25mA, 1.9 mGy
Custom-made wooden platform
A fresh frozen foot
Posterior talofibular ligament
Anterior talofibular ligament
Calcaneofibular ligament
| 29

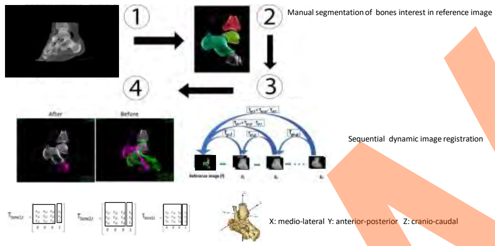

CADAVER EXPERIMENTS: QUALITATIVE EVALUATION OF LIGAMENT CUT

CADAVER EXPERIMENTS: QUANTITATIVE EVALUATION OF LIGAMENT CUT

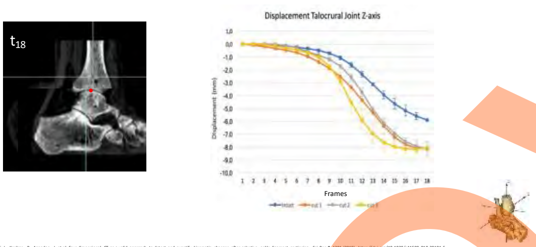
Obtaining quantitative kinematic information (cardan angles, dsplacements etc) is achieved by image processing techniques of Image segmentation and registration



CADAVER EXPERIMENTS: QUANTITATIVE EVALUATION OF LIGAMENT CUT

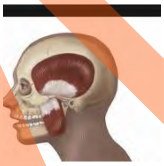


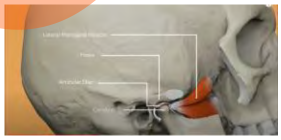
CADAVER EXPERIMENTS: QUANTITATIVE EVALUATION OF LIGAMENT CUT



Buzzatti, L., Keelson, B., Apperloo, J. *et al.* Four-dimensional CT as a valid approach to detect and quantify kinematic changes after selective ankle ligament sectioning. *Sci Rep* **9**, 1291 (2019). https://doi.org/10.1038/s41598-018-38101-5

THE TEMPOROMANDIBULAR JOINT (TMJ)





The joint consists of a hinge
And slide (rotation and translation) motion

TMJ problems affect up to one-third of all adults at some stage in their lives, as well as affecting children and adolescents.

CAUSES OF TMJ DISORDERS

- inflammatory and degenerative arthritis,
- trauma,
- infection
- complications of surgery

Courtesy CADskills

THE STUDY PURPOSE

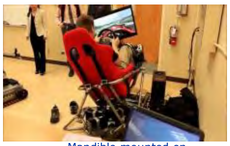
The purpose of this study was to investigate :

- **The potential use of dynamic CT for TMJ evaluation in a phantom study**

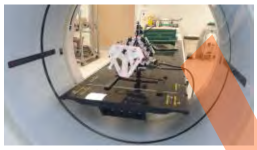
PHANTOM DESIGN

3D printed mandible based on segmented CT image

A 6DOF parallel manipulator based on the Stewart Platform Principle.

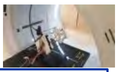


Mandible mounted on Stewart Platform



EXPERIMENTAL DESIGN

- Static scan
- Dynamic scan



mandibular depression | mandibular protrusion | laterotrusion left | laterotrusion right | mandibular retrusion | mandibular elevation

Scanning parameters

Tube voltage: 80kV, $CTDI_{vol}$: 63.95 mGy

Tue current: 50 mA, Slice. Thikcness:1.25 mm

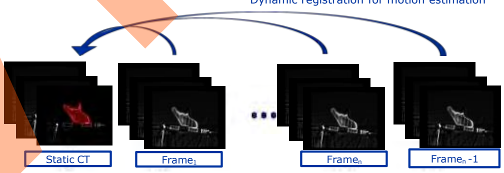
Collimation: 256 x 1.25 mm, Tube rotation time: 0.28 s

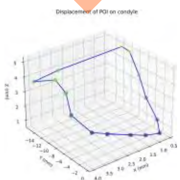
The phantom was scanned 5 times

DATA PROCESSING

Segmentation of mandible from Static CT image

Dynamic registration for motion estimation





PRESENCE OF MOTION ARTIFACTS FOR CERTAIN MANEUVERS

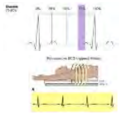
80 kV, 15 mA,0.28s, 25bpm

80 kV, 15 mA , 0.28s 35 bpm

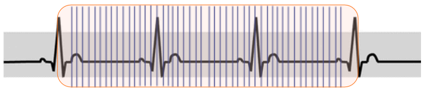
Knee cine acquisition 0.28s tube rotation time

Highlighting the need for further scan protocol optimization to minimise motion artifact
-especially for relatively fast motion

PROTOCOL OPTIMIZATION: LEVERAGING CARDIAC SCAN MODE FOR DYNAMIC MSK APPLICATIONS



- Requires ECG gating
  - Simulated heart rate of 30 bpm
  - Reconstructions @ 2% from 0 to 300%

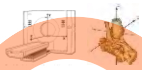


SCAN PROTOCOL OPTIMIZATION: CARDIAC SCAN MODE FOR DYNAMIC MSK APPLICATIONS

SUMMARY: SCAN PROTOCOL OPTIMIZATION

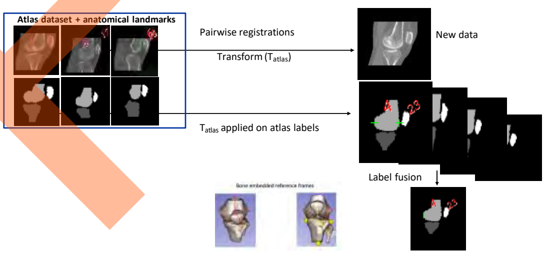
- ✓ Subtle changes in kinematics induced by ligament sectioning could be detected using a low dose protocol combined with a fast tube rotation time.
- ✓ Cardiac scan mode significantly ($p < 0.001$) reduced motion artifacts in both phantom images and dynamic images of the knee
- ✓ A low dose cardiac acquisition protocol can facilitate dynamic MSK imaging.

- × Need for a manual segmentations
- × Reference frame for motion is defined using the CT's global



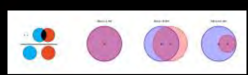
Ensure quality dynamic images as well as patient safety Scan protocol optimization	**Establish robust workflow for processing and analyzing the images** Image analysis	Explore clinical/pre-clinical applications of 4D CT based on previous experiences (Pre) clinical studies

IMAGE ANALYSIS: MULTI-ATLAS SEGMENTATION + ANATOMICAL LANDMARK IDENTIFICATION



Keelson, B., Buzzatti, L., Ceranka, J., Gutiérrez, A., Battista, S., Scheerlinck, T., ... & Vandemeulebroucke, J. (2021). Automated Motion Analysis of Bony Joint Structures from Dynamic Computer Tomography Images: A Multi-Atlas Approach. *Diagnostics*, *11*(11), 2062.

IMAGE ANALYSIS: RESULTS MULTI-ATLAS SEGMENTATION



Dice: 0.94 ± 0.01

Dice: 0.90 ± 0.01

IMAGE ANALYSIS:DYNAMIC REGISTRATION WORKFLOW

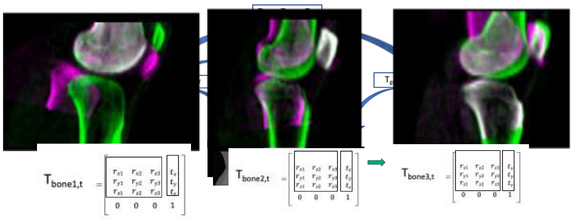
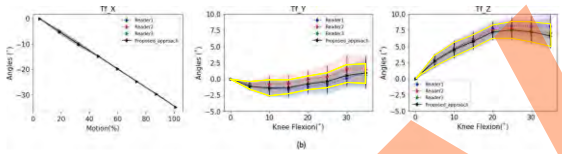


IMAGE ANALYSIS: RESULTS CARDAN ANGLES KNEE MOTION



SUMMARY: IMAGE ANALYSIS

MAS approach facilitated time gain in the segmentation of reference images for the dynamic registration framework and anatomical landmark propagation.

We have a low dose protocol which minimizes motion artifact combined with a robust image analysis workflow that performs on par to three expect readers

Ensure quality dynamic images as well as patient safety

Scan protocol optimization

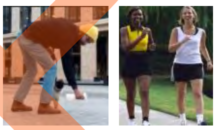
Establish robust workflow for processing and analyzing the images

Image analysis

Explore clinical/pre-clinical applications of 4D CT based on previous experiences

(Pre) clinical studies

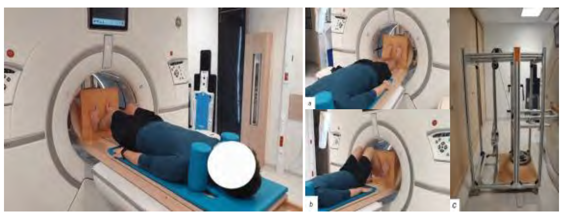
KNEE AND PATELLAR MOTION IN WEIGHT-BEARING CONDITIONS



The lower extremities primarily experience weight-bearing conditions in most daily activities

Investigating lower limb dynamic activities on conventional CT's (supine systems) is challenging in load bearing conditions.

KNEE AND PATELLAR MOTION IN WEIGHT-BEARING CONDITIONS

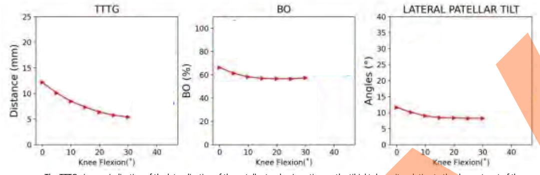


KNEE AND PATELLAR MOTION IN WEIGHT-BEARING CONDITIONS

- Twenty-one adult healthy volunteers, 12 females and 9 males
- Participants reported no symptoms during activities of daily living in the last 6 months.

CONTRIBUTIONS

RESULTS: KNEE AND PATELLAR MOTION IN WEIGHT-BEARING CONDITIONS



The TTTG gives an indication of the lateralization of the patellar tendon insertion on the tibial tuberosity relative to the deepest part of the trochlear groove (above 15 mm is generally considered pathological)

BO and LPT estimates the position and inclination (tilt) of the patella relative to the femur (LPT angle ≥15.0°, and a BO ≥57.0% are reported to be associated with pain)

E. M. Macri, D. T. Felson, Y. Zhang, A. Guermazi, F. W. Roemer, K. M. Crossley,K. M. Khan, and J. J. Stefanik, "Patellofemoral morphology and alignment:reference values and dose–response patterns for the relation to MRI features of patellofemoral osteoarthritis," Osteoarthritis and cartilage, vol. 25, no. 10, pp. 1690– 1697, 2017.
Jibri Z, Jamieson P, Rakhra KS, Sampaio ML, Dervin G. Patellar maltracking: an update on the diagnosis and treatment strategies. Insights into imaging. 2019 Dec;10:1-1.

TRAPEZIO-METACARPAL JOINT

- Fifteen adult healthy volunteers, 7 females and 8 males
- Participants reported no symptoms during activities of daily living in the last 6 months.
- Opposition reposition motion of the thumb

DYNAMIC CT APPLICATIONS: MUSCKULOSKELETAL

How do we present the data to the clinician?

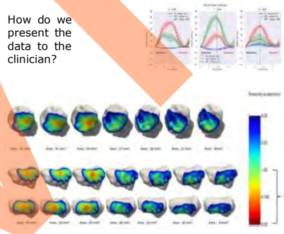
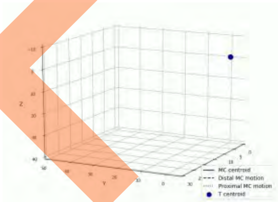


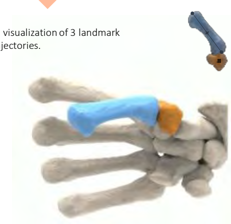
Image processing pipeline to obtain relevant **biokinetic parameters** of the joint movement

CONTRIBUTIONS

TRAPEZIO-METACARPAL JOINT KINEMATICS

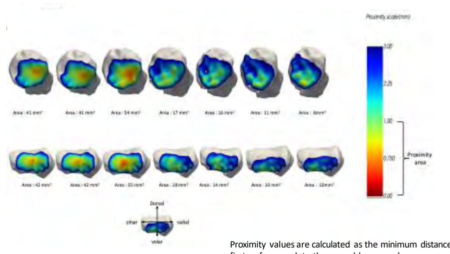


3D visualization of 3 landmark trajectories.



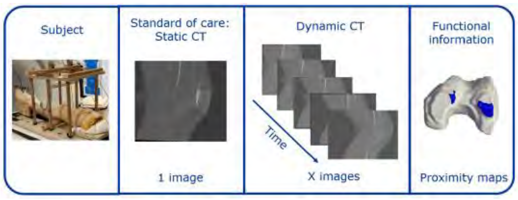
polygonal meshes were generated from the segmented bone for all time points

TRAPEZIO-METACARPAL JOINT PROXIMITY MAPS



Proximity values are calculated as the minimum distance from all mesh vertices on the first surface mesh to the second bone mesh.

GOAL OF THE STUDY



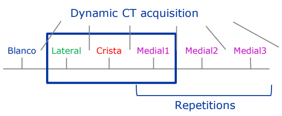
[1]

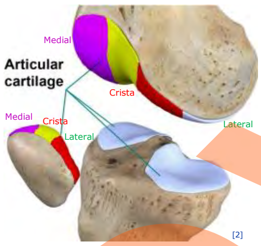
INTRODUCTION

GOAL OF THE STUDY

INTRODUCTION

INTERVENTIONS



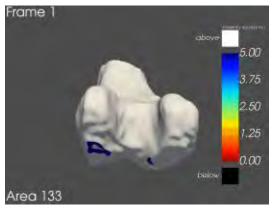


[2]

MATERIALS & METHODS

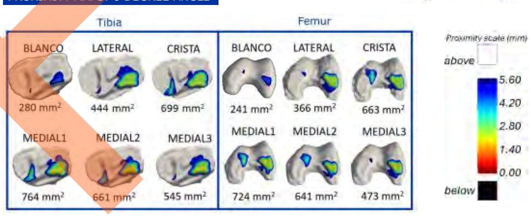
POST-PROCESSING: PROXIMITY MAPS

Distance < cartilage thickness



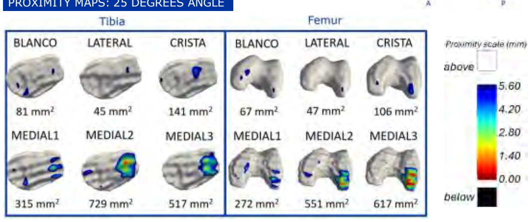
RESULTS

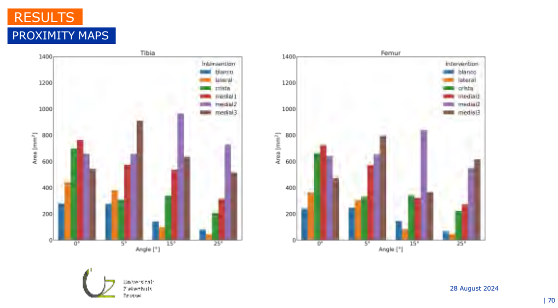
PROXIMITY MAPS: 0 DEGREE ANGLE

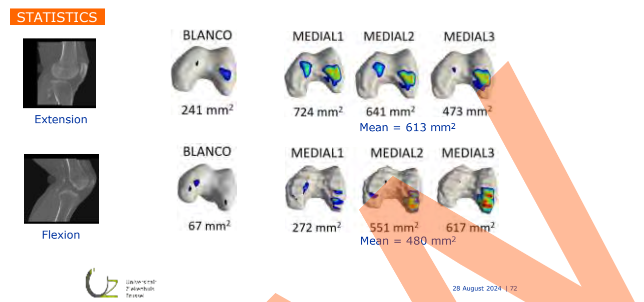


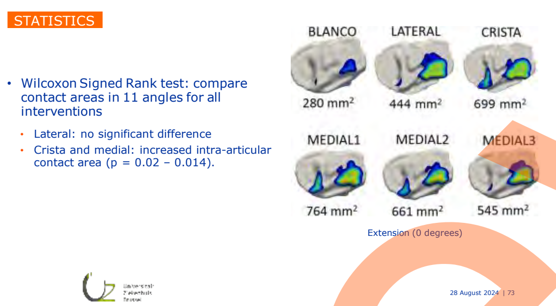
RESULTS

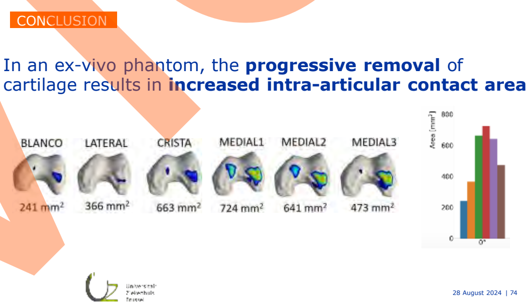
PROXIMITY MAPS: 25 DEGREES ANGLE

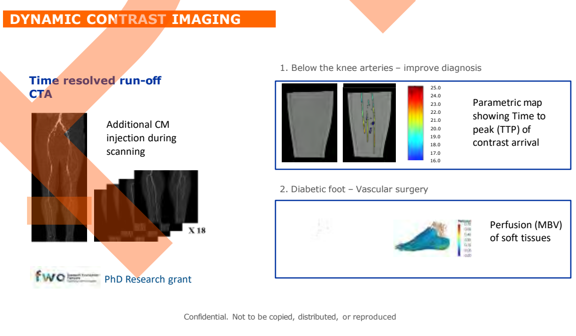


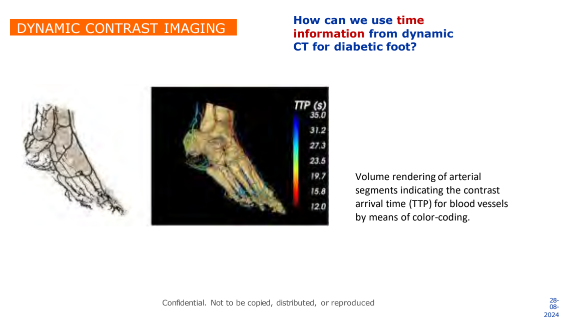

RESULTS
PROXIMITY MAPS
Tibia
Femur
Intervention
blanco
lateral
crista
medial1
medial2
medial3
Area [mm²]
Angle [°]
28 August 2024
| 70


STATISTICS
Extension
Flexion
BLANCO
MEDIAL1
MEDIAL2
MEDIAL3
241 mm²
724 mm²
641 mm²
473 mm²
Mean = 613 mm²
BLANCO
MEDIAL1
MEDIAL2
MEDIAL3
67 mm²
272 mm²
551 mm²
617 mm²
Mean = 480 mm²
28 August 2024 | 72


STATISTICS
• Wilcoxon Signed Rank test: compare contact areas in 11 angles for all interventions
• Lateral: no significant difference
• Crista and medial: increased intra-articular contact area (p = 0.02 – 0.014).
BLANCO
LATERAL
CRISTA
280 mm²
444 mm²
699 mm²
MEDIAL1
MEDIAL2
MEDIAL3
764 mm²
661 mm²
545 mm²
Extension (0 degrees)
28 August 2024 | 73


CONCLUSION
In an ex-vivo phantom, the progressive removal of cartilage results in increased intra-articular contact area
BLANCO
LATERAL
CRISTA
MEDIAL1
MEDIAL2
MEDIAL3
241 mm²
366 mm²
663 mm²
724 mm²
641 mm²
473 mm²
28 August 2024 | 74


DYNAMIC CONTRAST IMAGING
Time resolved run-off CTA
Additional CM injection during scanning
X 18
1. Below the knee arteries – improve diagnosis
Parametric map showing Time to peak (TTP) of contrast arrival
2. Diabetic foot – Vascular surgery
Perfusion (MBV) of soft tissues
PhD Research grant
Confidential. Not to be copied, distributed, or reproduced


DYNAMIC CONTRAST IMAGING
How can we use time information from dynamic CT for diabetic foot?
TTP (s)
35.0
31.2
27.3
23.5
19.7
15.8
12.0
Volume rendering of arterial segments indicating the contrast arrival time (TTP) for blood vessels by means of color-coding.
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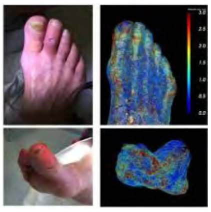
28-08-2024

DYNAMIC CONTRAST IMAGING

How can we use time information from dynamic CT for diabetic foot?



Volume rendering of blood flow (mL/g.s) parametric map at the level of the skin.

Elevated perfusion values in the areas of affected tissue.

Relative radiation doses

Source of Exposure	Dose
Dental X-ray	0.005mSv
135g of Brazil Nuts	0.005mSv
Chest X-ray	0.02mSv
Transatlantic flight	0.07mSv
Nuclear Power station worker, average annual dose	0.18mSv
UK average annual radon dose	1.3mSv
CT scan of the head	1.4mSv
UK average annual dose	2.7 mSv
CT scan of the chest	6.6 mSv
Whole body CT scan	10 mSv
Annual limit for nuclear radiation workers	20mSv
Level at which increased cancer incidence seen	100mSv
LD50 (within a month of exposure)	5000mSv

http://www.hpa.org.uk/Topics/Radiation/UnderstandingRadiation/UnderstandingRadiationTopics/DoseComparisonsForIonisingRadiation/

THANK YOU!

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Prof. Dr. Johan de Mey
Prof. Dr. Nico Buls
Prof. Dr. Jef Vandemeulebroucke
Prof. Dr. Thierry Scheerlinck
Prof. Dr. Jean-Pierre Baeyens
Prof. Dr. Gert Van Gompel
Prof. Dr. Michel de Maeseneer
Prof. Dr. Erik Cattrysse
Dr. Jakub Ceranka
Dr. Tjeerd Jager
Dr. Stijn Huys

VRIJE UNIVERSITEIT BRUSSEL
Universitair Ziekenhuis Brussel

Part 4 Advanced biomechanics & clinical analysis

1 EMG and posturography

: Biomedical signals and Images

1.1 EMG

1.1.1 Introduction of bio-electricity

1.1.2 Muscles and the EMG

1.1.3 Measurement and processing

1.1.4 Others

1.1.5 Factors influencing the EMG signal

1.1.6 EMG as a diagnostic tool

1.2 Posturography

: Posturography

1.2.1 Introduction

1.2.2 Analyzing the stabilogram

1.2.3 How does a force plate work?

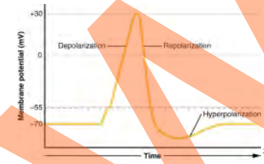
1.2.4 Improving patient rehabilitation techniques

1.3 Additional information, slides, articles

0. BIO-ELECTRICITY IN 1 SLIDE

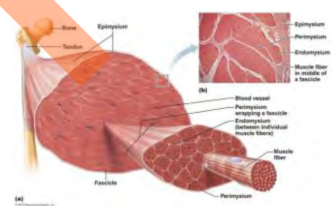
Cell depolarization

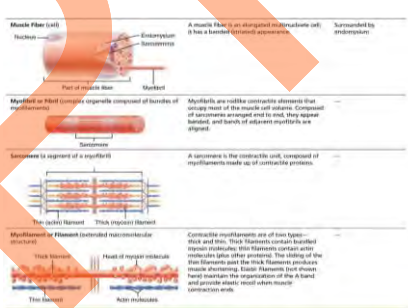
- Many cells maintain an interior negative charge compared to the cell's exterior = membrane potential.
  - e.g. 3 Na^+ pumped out of the cell for every two K^+ ions pumped in.
- Depolarization is the process of – quickly – shifting from negative to positive charge.
  - e.g. Na^+ rushes back into the cell
- Repolarization: initial potential is established again.
  - e.g. K^+ flows out

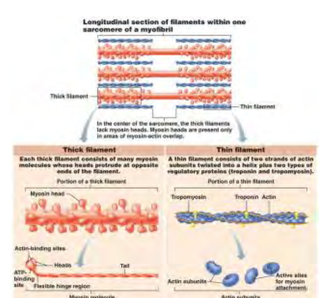


I. MUSCLES AND THE EMG

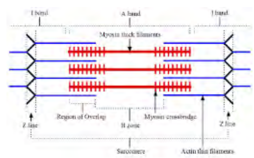
The anatomy of the muscle





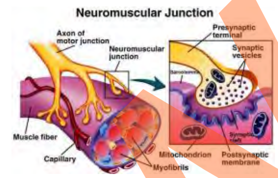


Binding of myosin and actin shortens the sarcomere length = muscle contraction

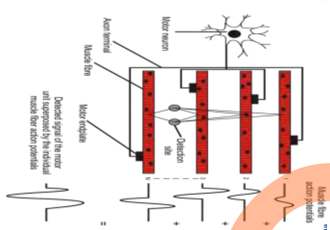


Steps in generating the action potential at the muscle fibers

- Cns
- Motor neuron
- Synapse
- Cell depolarization
- Action potential



From fiber AP to motor unit AP



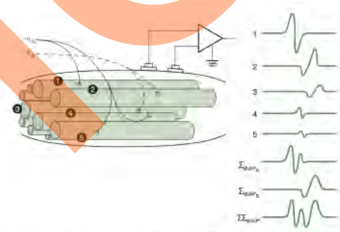
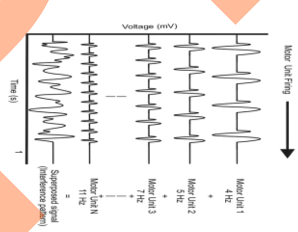


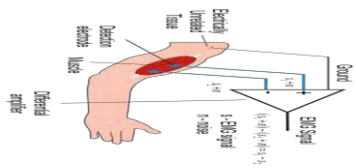
Figure 8.2 The contribution that each fiber's AP makes to the EMG signal depends in large part on the depth of the fiber; note that fiber 5 contributes a smaller AP than fiber 1. The temporal characteristics of the signal also depend on the electrode–motor endplate distance as well as the terminal lengths and diameters of the moto-neurons. Two motor units are shown here, with the amplitude of each motor unit represented as the algebraic sum of the individual muscle fiber APs (Σ_{MUAP}). The overall signal is the algebraic sum of all motor units ($\Sigma\Sigma_{MUAP}$).

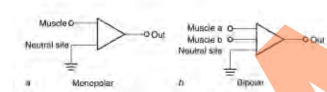
Superimposition of motor unit potentials



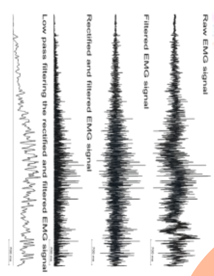
MEASUREMENT AND PROCESSING

Measurement of EMG





Processing

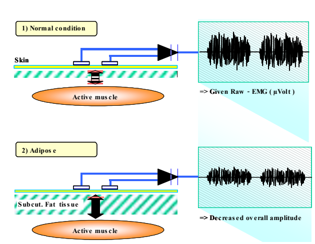


Others

- A/D resolution
- Amplifiers
- Electrodes

FACTORS INFLUENCING THE EMG SIGNAL

Tissue characteristics

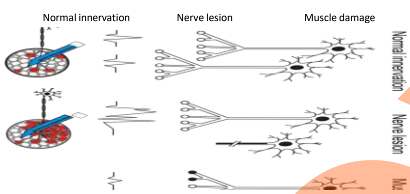


Physiological crosstalk

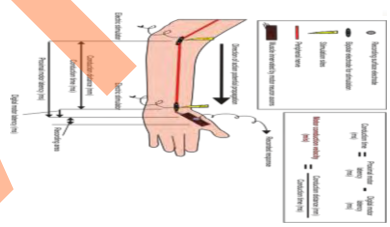
- Electrodes might capture activity from other neighbouring muscles

EMG AS A DIAGNOSTIC TOOL

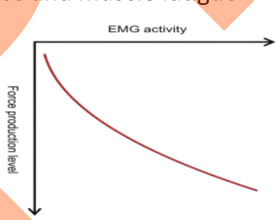
Muscular and neurological lesions



Muscle conductivity



Muscle Force and muscle fatigue



POSTUROGRAPHY

Bart Jansen

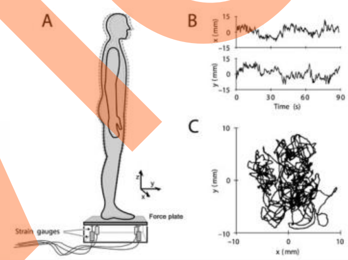
VRIJE UNIVERSITEIT BRUSSEL

POSTUROGRAPHY

- Dynamic Posturography characterizes the performance of the postural control system by measuring the postural response to an applied postural perturbation
- Static Posturography characterizes the performance of the postural control system in a static condition and environment during quiet standing.
- Eyes open / eyes closed and both legs / single leg.
- Prieto et al, 1996

MEASURING WITH A FORCE PLATE

In biomechanics, **center of pressure** (CoP) is the term given to the point of application of the ground reaction force vector. The ground reaction force vector represents the sum of all forces acting between a physical object and its supporting surface. (Wikipedia)



Mediolateral and anterioposterior displacement of COP

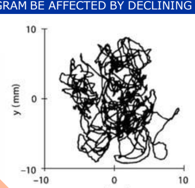
Stabilogram

https://www.mdpi.com/1660-4601/18/5/2696

ANALYZING THE STABILOGRAM

WHAT DO WE NEED TO ANALYSE?

HOW CAN THE STBILOGRAM BE AFFECTED BY DECLINING BALANCE?



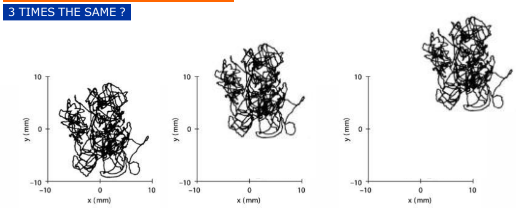
TO BE DONE PROPERLY

Table 1. Variables for global analysis of center of pressure (CP) and codes to calculate these variables using the Matlab programming environment.

Variable	Description	Matlab Code
Total displacement of sway, DOT	'Size' or length of CP trajectory on the base of support	DOT=sum(sqrt(CPap.^2+CPml.^2));
Standard deviation	Dispersion of CP displacement from the mean position during a time interval	SDap=std(CPap); SDml=std(CPml);
RMS ('root mean square')	If the CP signal has zero mean, RMS and standard deviation provide the same result	RMSap=sqrt(sum(CPap.^2)/length(CPap)); RMSml=sqrt(sum(CPml.^2)/length(CPml));
Amplitude of CP displacement	Distance between the maximum and minimum CP displacement for each direction	AdCPap=max(CPap) - min(CPap); AdCPml=max(CPml) - min(CPml);
Mean velocity (MV)	Determine how fast were the CP displacements	MVap=sum(abs(diff(CPap)))*freq/length(CPap) MVml=sum(abs(diff(CPml)))*freq/length(CPml)
Area	[vec,val]=eig(cov(CPap,CPml)); Area=pi*prod(2.4478*sqrt(svd(val)))	
Total mean velocity (TMV)	TMV=sum(sqrt(diff(CPap).^2+diff(CPml).^2))*freq/length(CPap)	

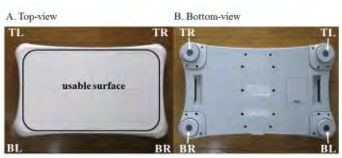
ANALYZING THE STABILOGRAM

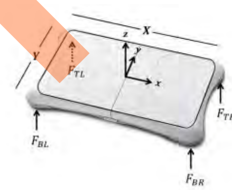
3 TIMES THE SAME ?



HOW DOES A FORCE PLATE WORK?

THE WII BALANCE BOARD AS A SIMPLE MODEL





X = 433mm, Y=238mm

$$CoP_{WBB_x} = \frac{X}{2}\frac{(F_{TR}+F_{BR})-(F_{TL}+F_{BL})}{F_{TR}+F_{BR}+F_{TL}+F_{BL}};\ CoP_{WBB_y} = \frac{Y}{2}\frac{(F_{TR}+F_{TL})-(F_{BR}+F_{BL})}{F_{TR}+F_{BR}+F_{TL}+F_{BL}}$$

STANDING BALANCE, EYES OPEN, 30S, N=15, AGE 24(2)

YOUNG HEALTHY VOLUNTEERS

	WBB	FP	ICC
DOT	32 (11)	37 (13)	0.92
AREA	64 (34)	81 (38)	0.97
RMS AP	1.4 (0.63)	1.6 (0.74)	0.97
RMS ML	2.6 (0.84)	3.0 (0.91)	0.91
AdCP AP	7.2 (3.2)	8.4 (3.7)	0.95
adCP ML	12.1 (3.8)	13.8 (4.1)	0.93
MV ap	6.3 (1.9)	5.9 (3.1)	0.93
MV ml	8.0 (2.4)	8.5 (2.7)	0.98
TMV	11.3 (3.3)	11.6 (4.5)	0.96

Bonnechère et al. ICT for improving patient rehabilitation techniques. 2015

2 Applied biomechanics (Prof. Dr. Marc Degelaen)

: Applied biomechanics

2.1 Introduction

2.2 Motor skills coordination

2.3 Cerebral palsy

2.4 Clinical gait analysis

2.4.1 Introduction

2.4.2 Instrumented

2.4.3 Technology coordination

2.4.4 Kinematics

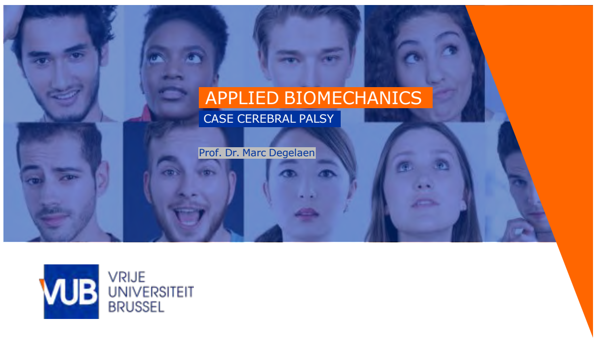
2.4.5 Plots

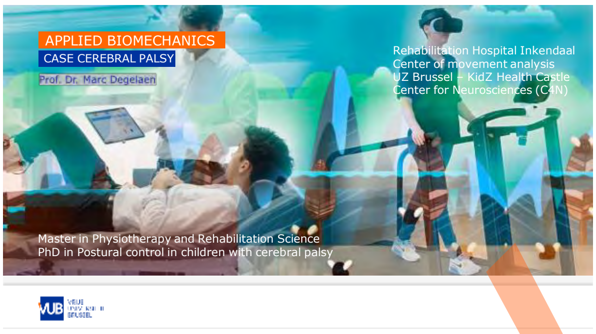
2.4.6 Interjoint vs intersegmental coordination

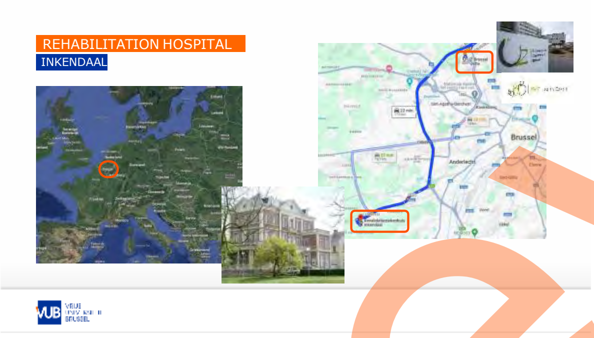
2.4.7 Mean absolute relative phase (MARP)

2.5 Case studies

2.6 Additional information, slides, articles

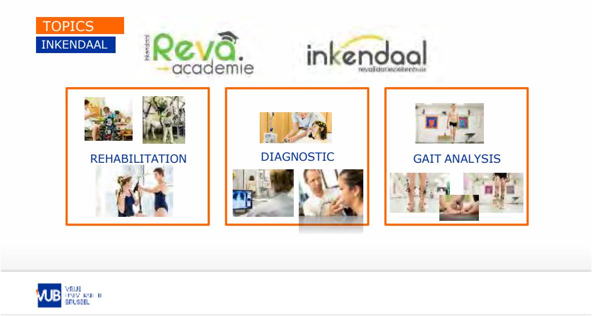

APPLIED BIOMECHANICS
CASE CEREBRAL PALSY
Prof. Dr. Marc Degelaen
VUB
VRIJE UNIVERSITEIT BRUSSEL


APPLIED BIOMECHANICS
CASE CEREBRAL PALSY
Prof. Dr. Marc Degelaen
Rehabilitation Hospital Inkendaal
Center of movement analysis
UZ Brussel – KidZ Health Castle
Center for Neurosciences (C4N)
Master in Physiotherapy and Rehabilitation Science
PhD in Postural control in children with cerebral palsy


REHABILITATION HOSPITAL
INKENDAAL
Brussel


INPATIENT
OUTPATIENT
REHABILITATION HOSPITAL
INKENDAAL
inkendaal
Pediatric Rehabilitation & School
Acquired Brain Injury
Chronic Neurological Disorders
Locomotor rehabilitation

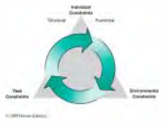

REHABILITATION HOSPITAL
INKENDAAL
Werking Inkendaal
Kind en familie
inkendaal


TOPICS
INKENDAAL
Reva academie
inkendaal
REHABILITATION
DIAGNOSTIC
GAIT ANALYSIS

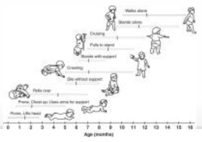
MOTOR SKILLS COORDINATION

THEORETICAL BACKGROUND

✓ DTS

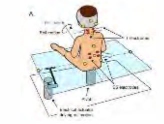


✓ Motor competence (MC)



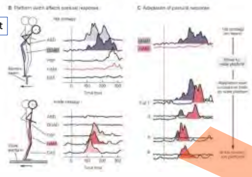
MOTOR CONTROL

Posture | Movement



Acquisition of independent walking plays a role in the development of anticipatory postural control, likely improving the internal model for the sensorimotor control of posture

✓ PA & APA



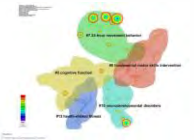
✓ CPG and sensory feedback

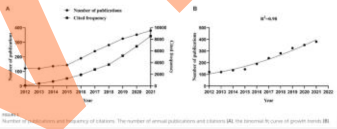
Figure 4.21 Walking cycle of a human. The arms and legs must be coordinated in opposing fashion during locomotion. The gray hand and foot are left side limbs. When one is in front of the body, the other is behind. "Walking Cycle" by Cassie Bishop is licensed under a Creative Commons Attribution Non-Commercial Share Alike (CC BY-NC-SA) 4.0 International License.

MOTOR SKILLS RESEARCH

Global hotspots and trends in research on preschool children's motor development from 2012 to 2022: a bibliometric analysis

Jun-Wei Wang[1,2], Sha Qu[1], Zhi-Cheng Zhu[1], Xing Zhao[1], Wen-Jing Song[1], Xue Li[1], Wan-Di Chen[1] and Dong-Mei Luo*





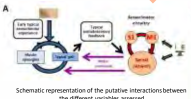
PATHOLOGY

CP/ DCD

From cerebral palsy to developmental coordination disorder: Development of preclinical rat models corresponding to recent epidemiological changes

Jacques-Olivier Coq, Marine Kochmann, Diego Lacerda, Hanane Khalki, Maxime S Delcour, Ana Toscano, Florence Cayetanot, Marie-Hélène Canu, Mary F Barbe, Masahiro Tsuji

Illustration of the putative interactions and processes underlying the emergence of movement disorders and brain plasticity



Schematic representation of the putative interactions between the different variables assessed

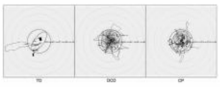
Schematic illustration of the detrimental impact of mild intrauterine hypoperfusion on neuromuscular interplay and brain disorganization.

Schematic illustration of the deleterious impact of postnatal sensorimotor restriction (SMR) on neuromuscular interplay

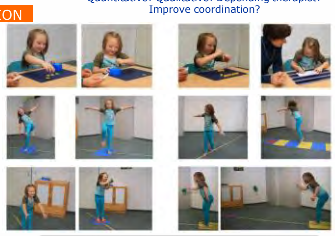
MEASUREMENT COORDINATION

TOOLS ?

Quantitative? Qualitative? Depending therapist?
Improve coordination?



The sway area meaning the distribution of the COP during the trial is presented, with one representative case for each group: on the left a TD subject with the smallest area, in the center and on the right, a subject with DCD and one with CP, respectively.

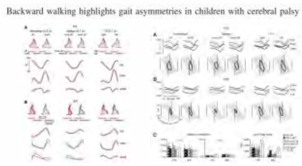


Application of Virtual Reality Rehabilitation System for the assessment of postural control while standing in typical children and peers with neurodevelopmental disorders

Elena Beani, Silvia Filogna, Giada Martini, Veronica Barzacchi, Adriano Ferrari, Elisa Guidi, Valentina Menici, Giovanni Cioni, Giuseppina Sgandurra

MOTOR COORDINATION

STRATEGY



Examples of gait kinematics children during Forwards (A) and backwards Walking (B). Stick diagrams of the swing phase of a single step for both legs, limb contact patterns of the 2 consecutive cycles

Planar covariation of limb segment elevation angles during Forward en backwards Walking foot, thigh, and shank elevation angles plotted vs. the normalized gait cycle.

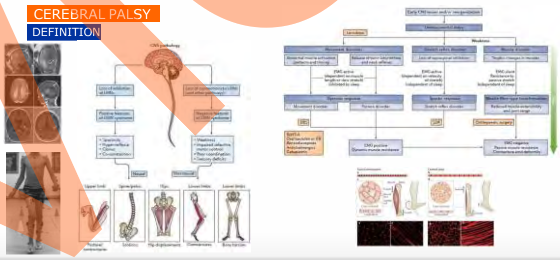
EXAMPLES

STRATEGY

CEREBRAL PALSY

CEREBRAL PALSY

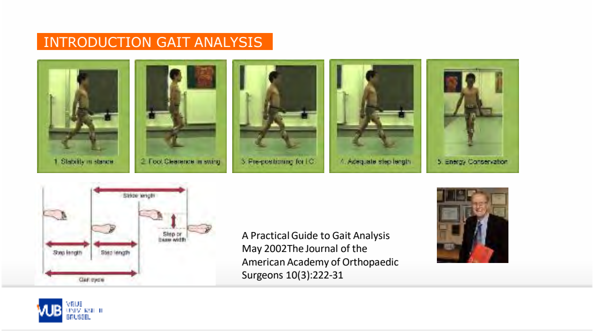
DEFINITION

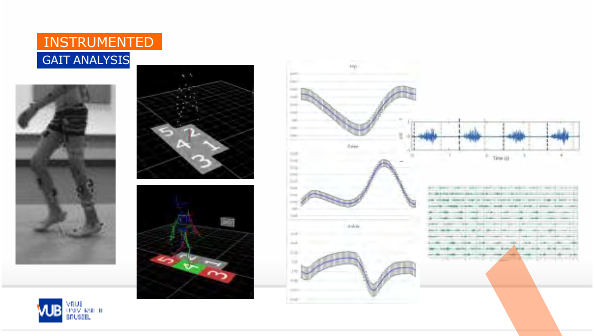


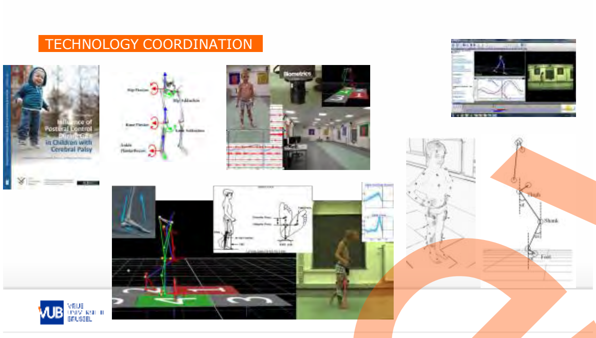
EXAMPLES

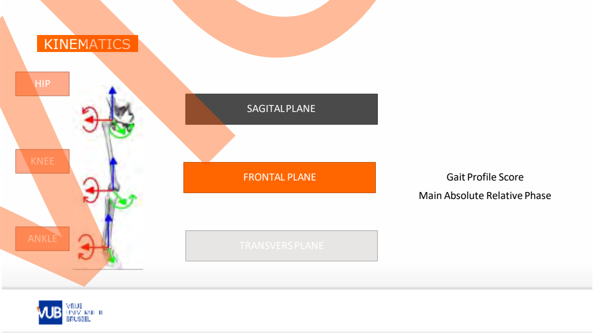
WALKING

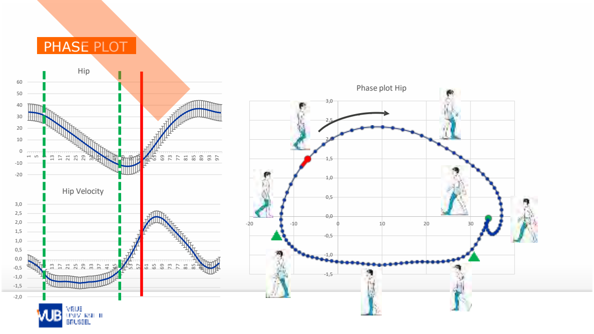
CLINICAL GAIT ANALYSIS

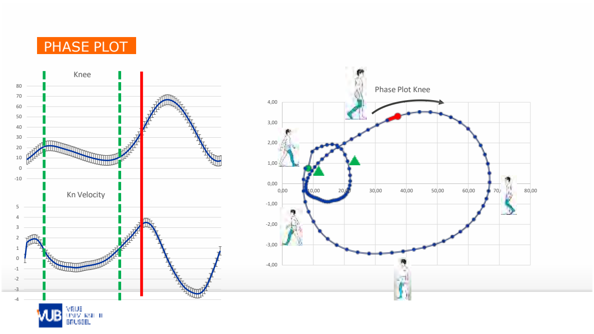

INTRODUCTION GAIT ANALYSIS
1. Stability in stance
2. Foot Clearance in swing
3. Pre-positioning for I C
4. Adequate step length
5. Energy Conservation
Stride length
Step length
Step length
Step or base width
Gait cycle
A Practical Guide to Gait Analysis
May 2002The Journal of the
American Academy of Orthopaedic
Surgeons 10(3):222-31

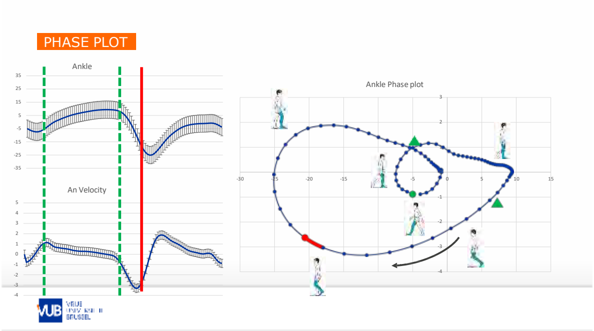

INSTRUMENTED
GAIT ANALYSIS

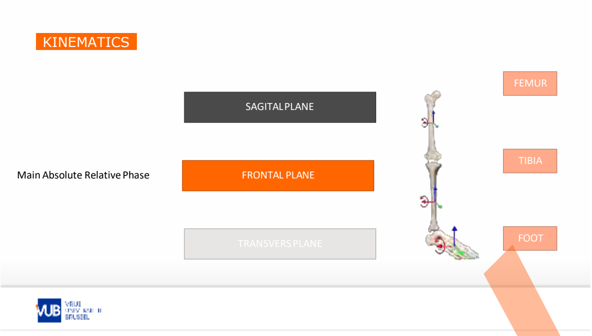

TECHNOLOGY COORDINATION

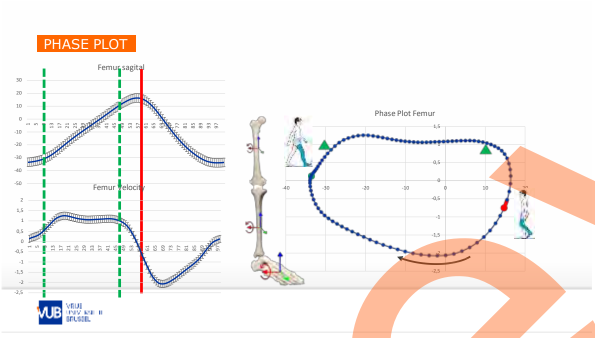

KINEMATICS
HIP
KNEE
ANKLE
SAGITAL PLANE
FRONTAL PLANE
TRANSVERS PLANE
Gait Profile Score
Main Absolute Relative Phase


PHASE PLOT
Hip
Hip Velocity
Phase plot Hip

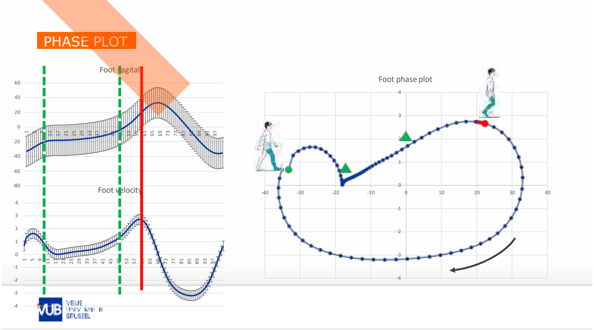

PHASE PLOT
Knee
Kn Velocity
Phase Plot Knee

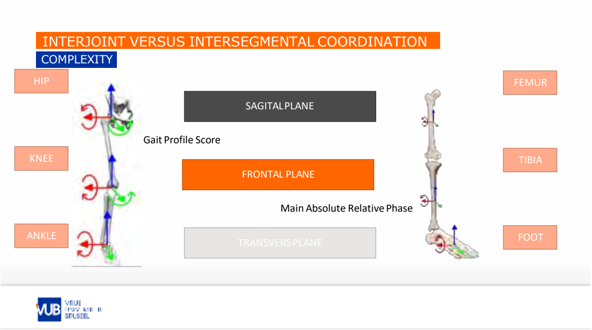

PHASE PLOT
Ankle
An Velocity
Ankle Phase plot


KINEMATICS
SAGITAL PLANE
Main Absolute Relative Phase
FRONTAL PLANE
TRANSVERS PLANE
FEMUR
TIBIA
FOOT

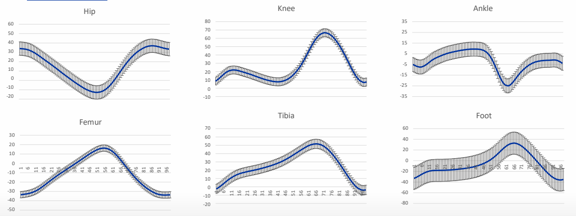

PHASE PLOT
Femur sagital
Femur velocity
Phase Plot Femur


PHASE PLOT
Tibia sagital
Tibia Velocity Sagital
Tibia Phase Plot

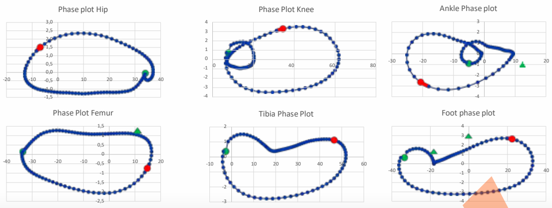

PHASE PLOT
Foot sagital
Foot velocity
Foot phase plot


INTERJOINT VERSUS INTERSEGMENTAL COORDINATION
COMPLEXITY
HIP
KNEE
ANKLE
SAGITAL PLANE
Gait Profile Score
FRONTAL PLANE
Main Absolute Relative Phase
TRANSVERS PLANE
FEMUR
TIBIA
FOOT

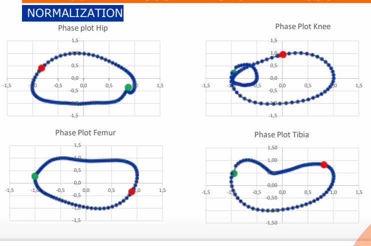
INTERJOINT VERSUS INTERSEGMENTAL COORDINATION
KINEMATICS



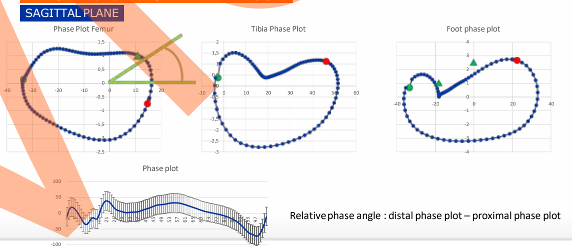
INTERJOINT VERSUS INTERSEGMENTAL COORDINATION
PHASE PLOTS



INTERJOINT VERSUS INTERSEGMENTAL COORDINATION
NORMALIZATION

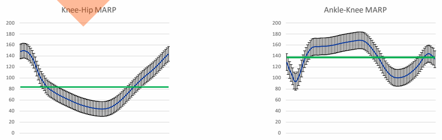


PHASE PLOTS FEMUR – TIBIA – FOOT
SAGITTAL PLANE



Relative phase angle : distal phase plot – proximal phase plot

MEAN ABSOLUTE RELATIVE PHASE (MARP)
RELATIVE PHASE

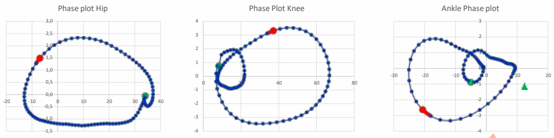


CASE CEREBRAL PALSY

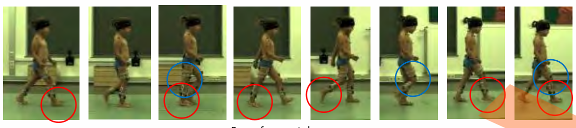
CASE A

PHASE PLOTS HIP – KNEE – ANKLE

SAGITTAL PLANE



GAIT

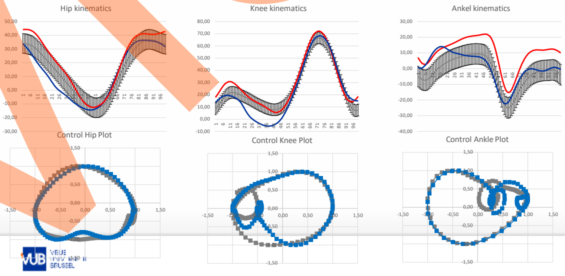


Base of support ↓

Foot clearance ↓ Early heel rise Foot clearance ↓ Foot clearance ↓

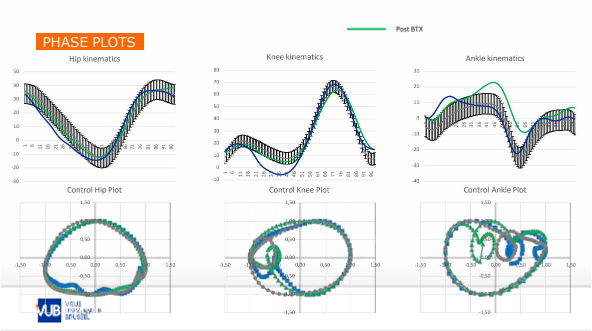
Knee extension ↑ Knee flexion ↑ Knee extension ↓

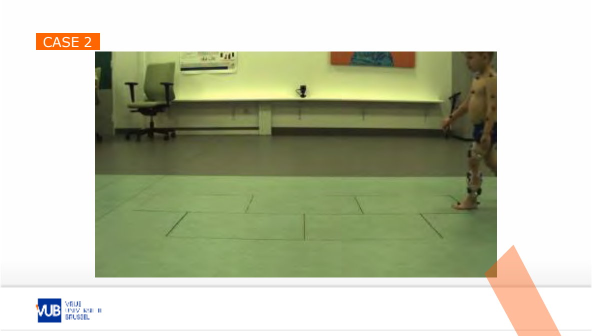
KINEMATICA

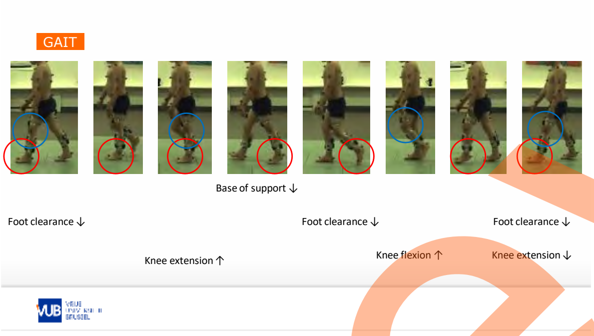


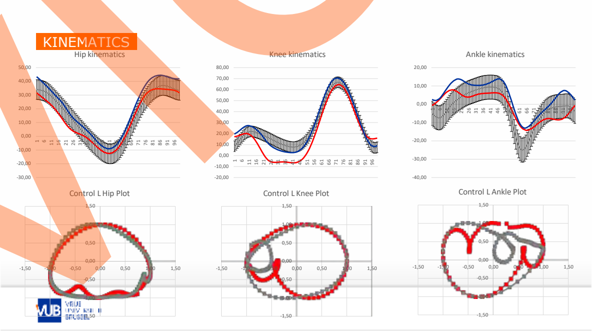
CASE A EVALUATION

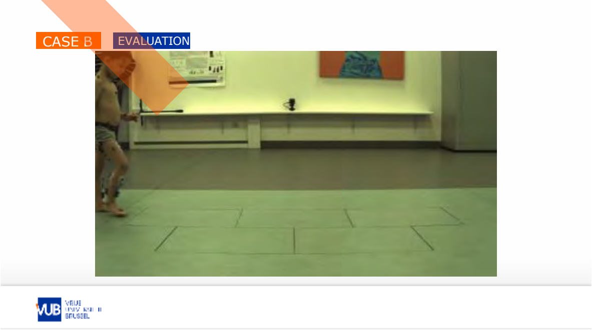
GAIT PRE BTX / POST BTX

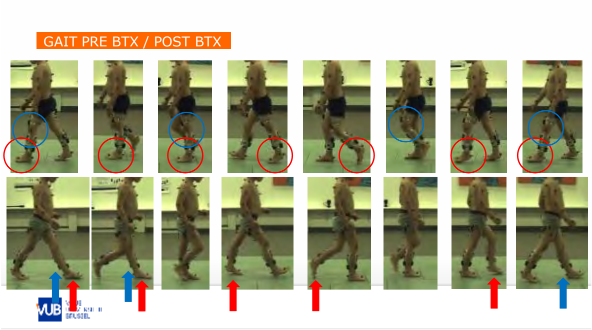

PHASE PLOTS
Post BTX
Hip kinematics
Knee kinematics
Ankle kinematics
Control Hip Plot
Control Knee Plot
Control Ankle Plot

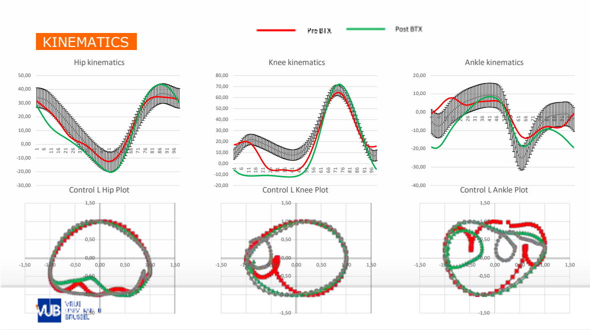

CASE 2

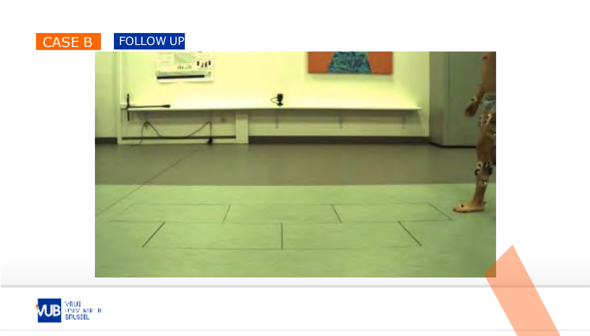

GAIT
Base of support ↓
Foot clearance ↓
Foot clearance ↓
Foot clearance ↓
Knee extension ↑
Knee flexion ↑
Knee extension ↓

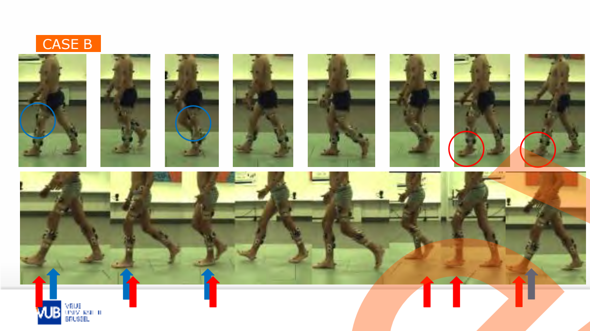

KINEMATICS
Hip kinematics
Knee kinematics
Ankle kinematics
Control L Hip Plot
Control L Knee Plot
Control L Ankle Plot

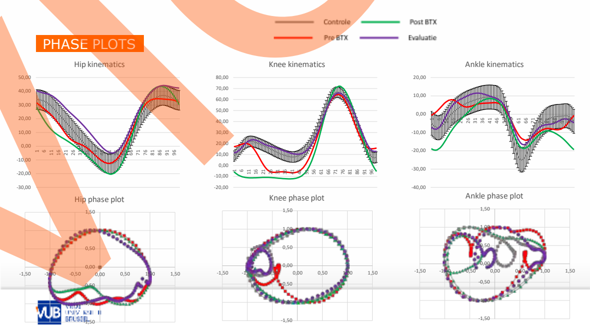

CASE B
EVALUATION

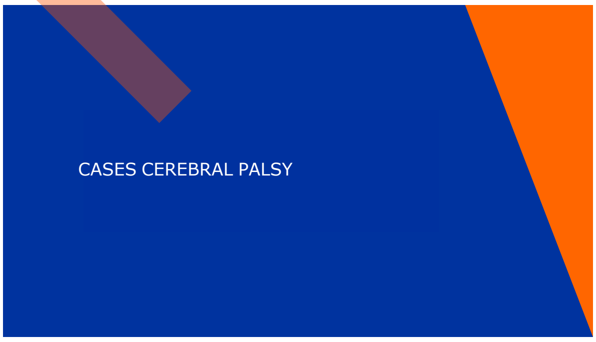

GAIT PRE BTX / POST BTX

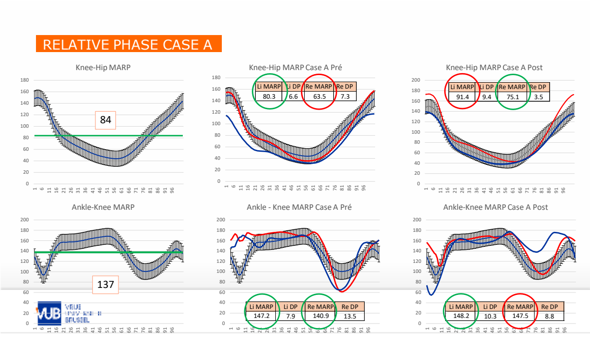

KINEMATICS
Pre BTX
Post BTX
Hip kinematics
Knee kinematics
Ankle kinematics
Control L Hip Plot
Control L Knee Plot
Control L Ankle Plot

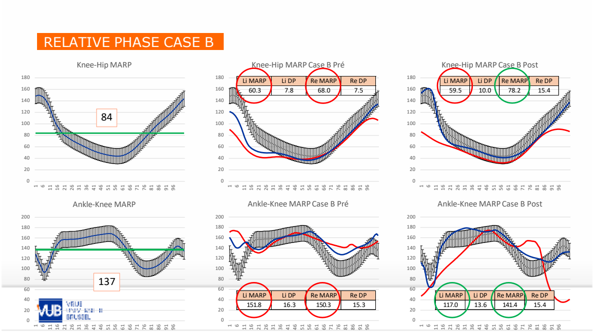

CASE B
FOLLOW UP

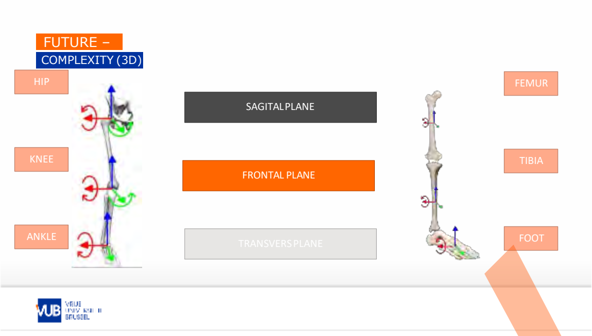

CASE B


PHASE PLOTS
Controle
Post BTX
Pre BTX
Evaluatie
Hip kinematics
Knee kinematics
Ankle kinematics
Hip phase plot
Knee phase plot
Ankle phase plot


CASES CEREBRAL PALSY


RELATIVE PHASE CASE A
Knee-Hip MARP
84
Knee-Hip MARP Case A Pré
Li MARP 80.3 Li DP 6.6 Re MARP 63.5 Re DP 7.3
Knee-Hip MARP Case A Post
Li MARP 91.4 Li DP 9.4 Re MARP 75.1 Re DP 3.5
Ankle-Knee MARP
137
Ankle - Knee MARP Case A Pré
Li MARP 147.2 Li DP 7.9 Re MARP 140.9 Re DP 13.5
Ankle-Knee MARP Case A Post
Li MARP 148.2 Li DP 10.3 Re MARP 147.5 Re DP 8.8

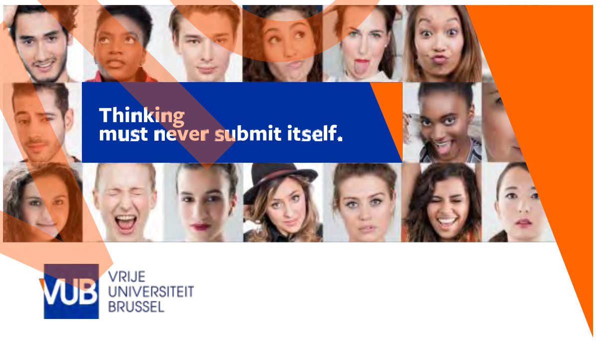




TAKE HOME MESSAGE

CONCLUSION

- botulinum toxin injection in lower limb spastic muscles leads to changes in motor planning
- Intersegmental coordination is a clinically important factor
- lower limb coordination parameters appear as relevant outcomes to quantify the adaptation of the locomotor system
- correlation between in-phase joint patterns and increased gait deviations (gait profile score) reinforces the relevance of coordination analysis to assess motor control impairment
- CRP analysis during gait distinguishes abnormal motion patterns associated with motor control challenges.
- examining and facilitating lower extremities inter-segmental coordination during walking could be an important factor in the development of rehabilitation interventions



3 Working sessions

3.1 Lab sessions IMU

- : Reader + extra documents on the learning platform

3.2 Intensive on campus week

- : See planning and documents on the learning platform

3.3 Additional information, slides, articles

Postgraduate Programme in 'Rehabilitation & Human Sustainable Technology'
MIAMI II
Processing and Analysis of IMU Walking Signal

Bart Jansen
Lecturer
bjansen@etrovub.be

Redona Brahimetaj
Teaching assistant
rbrahime@etrovub.be

In this lab session, we will explore, process and analyse Inertial Measurement Unit (IMU) signals, focusing specifically on human walking data. IMUs are important to understand human motion as they capture simple and/or complex movements through accelerometers and gyroscopes. An IMU sensor records movements which can offer insights into human motion patterns, essential for applications ranging from sports to rehabilitation. This session will provide hand-on experience by working with IMU data - from initial exploration to more advanced analysis - highlighing in such way the importance of signal processing techniques in extracting meaningful information from raw data.

1 Explore the IMU Data Files

1. Download the provided IMU data files. Open them using a text editor. How many columns are present, and what does each column represent? Identify the columns that represent the three axis (X-axis, Y-axis, Z-axis) of the accelerometer and gyroscope.

2. Write a python function to read the IMU data file into a pandas dataframe. Print the first five rows to verify the data is correctly loaded.

2 Vizualize the IMU Signals and Crop to the Walking Part

1. Using matplotlib, plot the three axis of an IMU accelerometer signal. Each axis should be plotted on the same graph. Add the labels for each axis, a title for your plot and a legend. Repeat same exercise by plotting also the corresponding gyroscope axis. Describe (via words) any observation you can make from the plot.

2. Can you visually identify the jumps performed? Why is it important to remove the part prior analyzing the walking data?

3. Based on your observation from the previous exercise, crop the IMU signal to only include the walking part. You may define the start and end points manually by inspecting the plot.

3 Analyze the Signal

1. Apply a low-pass filter to the cropped signal to smooth it out. You can use 'scipy' library for this purpose. Plot both the original cropped signal and the filtered one on the same graph. Describe the (visual) effect of the filtering (and of the used parameters) on the signal.

2. Use a peak detection function (i.e.: find_peaks) to detect peaks in both the original and the filtered signals. Plot the detected peaks on the graphs. Compare the number of peaks detected in the original vs the filtered one. Does filtering affect the detection of steps or peaks?

3. Modify your peak detection script to also identify the local maximas and the local minimas in the signal. Plot them on the graph of the filtered signal.

4. Discuss: (a) how the identification of local maxima and minima can provide insights into the walking pattern; (b) if/how it corresponds to significant gait events like Initial Contact (IC) and Final Contact (FC).

5. Considering the local maxima and minima you have found, do you think that is sufficient to rely to analyse gait patterns accurately? What limitations might arise from making assumptions without (correct) ground truth IC/FC detections?

6. How can we obtain ground truth data for IC and FC detections in walking patterns? Describe a method or system that could provide such information. Once the correlation between the IMU data points and the ground truth data for IC and FC is established, discuss how this information could be utilized in applications such as rehabilitation. What benefits would accurate detection of these gait events provide to us?

7. Create a python function that computes the step count, step time, step time std, cadence and side detection from the signal.

Useful links: Course material, Python, Pandas csv, Matplotlib plotting, Dataframe Slicing, Low-pass filtering, Peak detection.

Part 5 Clinical Applications, including remote rehabilitation for this lesson

1 Introduction to this part

How:

- online synchronous (live) (see online schedule)
- followed by (live) working sessions during the intensive on campus week (see schedule)

2 Virtual reality, augmented reality and serious gaming for rehabilitation: introduction

: Virtual Reality, augmented reality and serious gaming for rehabilitation

2.1 3 topics

2.1.1 Virtual reality

2.1.2 Augmented reality

2.1.3 Sensor Based gaming

3 Robotics for rehabilitation (Prof. Swinnen)

: Robotics for rehabilitation

3.1 Cases

3.2 How can we increase the effect of neurorehabilitation (applied to gait training)

3.3 Different systems for body weight support training and is effectivity

3.4 The need for guidelines

3.5 Examples of stationary technology

3.6 Examples of mobile technology

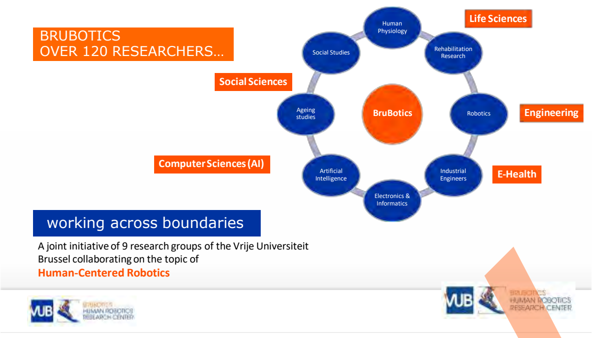
3.7 Trends and evolutions

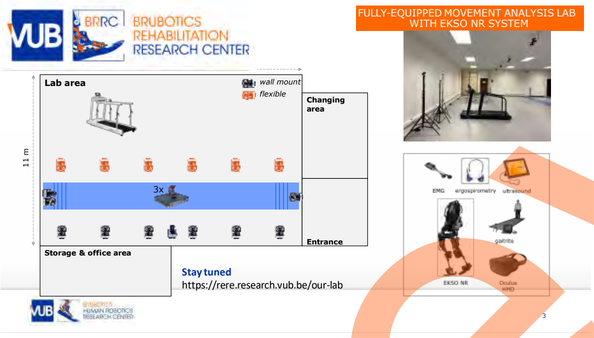
3.8 Combinations

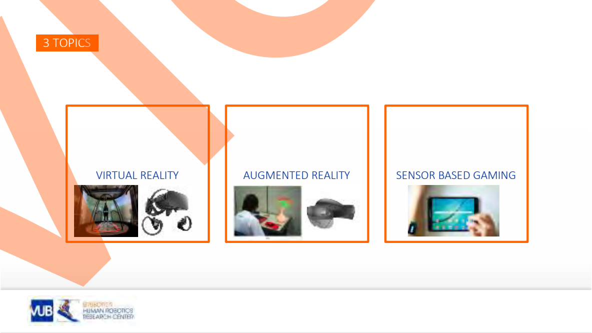
3.9 Telerehabilitation

3.10 Additional information, slides, articles


VUB VRIJE UNIVERSITEIT BRUSSEL
VUB RERE REHABILITATION RESEARCH GROUP
VIRTUAL REALITY, AUGMENTED REALITY AND SERIOUS GAMING FOR REHABILITATION
Prof. dr. Eva Swinnen
Master in Physiotherapy and Rehabilitation Science
PhD in robotic gait rehabilitation in neurological patients
Brussels Human Robotics Research Center (BRUBOTICS)
Center for Neurosciences (C4N)
I DECLARE THAT I HAVE NO CONFLICT OF INTEREST WITH RESPECT TO THE CONTENT OF THIS PRESENTATION.


BRUBOTICS
OVER 120 RESEARCHERS…
Human Physiology
Social Studies
Rehabilitation Research
Life Sciences
Social Sciences
Ageing studies
BruBotics
Robotics
Engineering
Computer Sciences (AI)
Artificial Intelligence
Industrial Engineers
E-Health
Electronics & Informatics
working across boundaries
A joint initiative of 9 research groups of the Vrije Universiteit Brussel collaborating on the topic of
Human-Centered Robotics


VUB BRRC BRUBOTICS REHABILITATION RESEARCH CENTER
FULLY-EQUIPPED MOVEMENT ANALYSIS LAB WITH EKSO NR SYSTEM
Lab area
wall mount
flexible
Changing area
11 m
3x
Entrance
Storage & office area
Stay tuned
https://rere.research.vub.be/our-lab
EMG
ergospirometry
ultrasound
gaitrite
EKSO NR
Oculus HMD
3


3 TOPICS
VIRTUAL REALITY
AUGMENTED REALITY
SENSOR BASED GAMING


NEED FOR TASK-SPECIFIC, REPETITIVE AND INTENSIVE TRAINING (FREIVOGEL ET AL. 2008, MEHRHOLZ ET AL. 2017)
Zzz
VR
Task-specific
Repetitive
Intensive
Monotonous training environment
5


VIRTUAL REALITY FOR REHABILITATION
FROM GAMING TOOL TO REHABILITATION TOOL
Increases relevant concepts of neural plasticity by providing training in more interactive and motivating environments
simulate dangerous, expensive or impossible real-life environments/situations
fully controllable
adaptable
VR

VIRTUAL REALITY FOR REHABILITATION

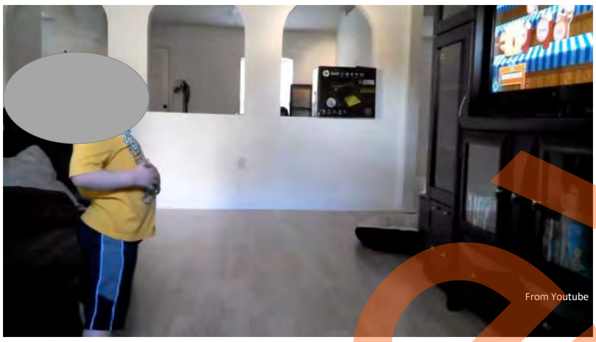
FROM GAMING TOOL TO REHABILITATION TOOL

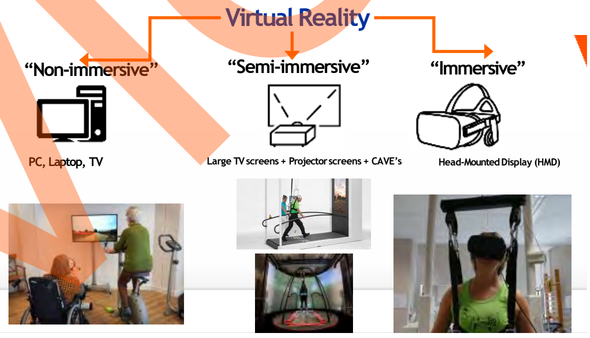
Increases relevant concepts of neural plasticity by providing training in more interactive and motivating environments

can increase patients' motivation
- → more repetitions
- → longer training durations
- → improving patients' treatment compliance

The use of virtual reality

Benefits vs Pitfalls





CASUS

Mrs. De Vries is a 76-year-old retired woman who used to be a saleswoman. She is an active lady who loves walking with her dog, visiting her friends and dancing with her husband. On Tuesday, September 5, 2019, Mrs. de Vries had agreed to meet a friend at 10 am. Her husband had left early that morning for the local market. However, Mrs. de Vries did not show up and her friend became worried. During her lunch break (around noon) her daughter went to see her mother and found her lying on the ground in the kitchen. Around the same time, Mr. De Vries also returned home. Mrs De Vries lay unconscious on the floor and there was an unpleasant smell in the kitchen. The daughter immediately called an ambulance, after which Mrs. de Vries was taken to the nearest hospital. There she first went to the intensive care unit, after which a surgical thrombectomy was performed (left cerebral artery area). Subsequently, Mrs. de Vries was transferred to the stroke unit at the Neurology department.

CASUS

Mrs. De Vries is a 76-year-old retired woman who used to be a saleswoman. She is an active lady who loves walking with her dog, visiting her friends and dancing with her husband. On Tuesday, September 5, 2019, Mrs. de Vries had agreed to meet a friend at 10 am. Her husband had left early that morning for the local market. However, Mrs. de Vries did not show up and her friend became worried. During her lunch break (around noon) her daughter went to see her mother and found her lying on the ground in the kitchen. Around the same time, Mr. De Vries also returned home. Mrs De Vries lay unconscious on the floor and there was an unpleasant smell in the kitchen. The daughter immediately called an ambulance, after which Mrs. de Vries was taken to the nearest hospital. There she first went to the intensive care unit, after which a surgical thrombectomy was performed (left cerebral artery area). Subsequently, Mrs. de Vries was transferred to the stroke unit at the Neurology department.

CASUS

STATUS 5 DAYS POST-STROKE

Would Virtual Reality applications be effective in this patient?

- ROM: normal left and right
- Muscle strength
  - Right arm: proximal 2/5, distal 2/5
  - Right leg: global 2/5
- Gait pattern: patient needs firm continuous support from therapist (FAC 1)
- Motricity Index: Upper limb 39/100 ; Lower limb 37/100
- Berg Balance Scale: 6/56
- Trunk control test: 62/100
- Barthel Index: 46/100
- No spasticity
- No sensory problems

Request for help: Mrs de Vries hopes that in the future she will no longer be dependent on others (for ADL and hygiene).

NeuroRehabilitation 44 (2019) 43–66
DOI:10.3233/NRE-182551
IOS Press

43

Review Article

Virtual reality during gait training: does it improve gait function in persons with central nervous system movement disorders? A systematic review and meta-analysis

Emma De Keersmaecker[a,b,c,*], Nina Lefeber[a,b,c], Marion Geys[a], Elise Jespers[a], Eric Kerckhofs[a,b,c] and Eva Swinnen[a,b,c]
[a]Rehabilitation Research – Neurological Rehabilitation, Department of Physiotherapy, Human Physiology and Anatomy, Vrije Universiteit Brussel, Brussels, Belgium
[b]Center for Neurosciences (C4N), Vrije Universiteit Brussel, Brussels, Belgium
[c]Brussels Human Robotic Research Center (BruBotics), Vrije Universiteit Brussel, Brussels, Belgium

HUMAN ROBOTICS RESEARCH CENTER 19

Is the use of virtual reality during gait training effective for individuals with central neurological movement disorders?

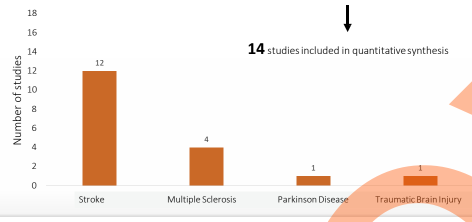
Does virtual reality have a greater effect than training without virtual reality?

HUMAN ROBOTICS RESEARCH CENTER 20

INCLUDED POPULATIONS

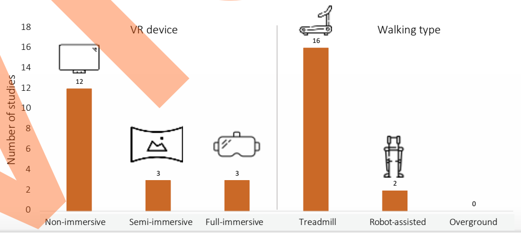
18 studies included in qualitative synthesis

14 studies included in quantitative synthesis



NeuroRehabilitation (2019) 21

INCLUDED VR INTERVENTIONS



NeuroRehabilitation (2019) 22

TRAINING WITH VR PRODUCED SIGNIFICANT IMPROVEMENTS IN GAIT FUNCTION

Stroke

Spatiotemporal gait parameters
Functional gait parameters

Significant, clinical relevant improvement

Improvements for walking speed (MD = 0.17 m/s), berg balance scale (MD = 3.83 points) and timed up and go (MD = 3.42 s) exceeded MCID

NeuroRehabilitation (2019) 23

TRAINING WITH VR PRODUCED SIGNIFICANT IMPROVEMENTS IN GAIT FUNCTION

Multiple Sclerosis

Spatiotemporal gait parameters
Functional gait parameters

Significant, clinical relevant improvement

Improvements for walking speed (MD = 0.11 m/s) and berg balance scale (MD = 4.65 points) exceeded MCID

NeuroRehabilitation (2019) 24

TRAINING WITH VR IS MORE EFFECTIVE THAN TRAINING WITHOUT VR

Stroke

Spatiotemporal gait parameters
Functional gait parameters

walking speed, cadence, step length, stride length, single limb support period, berg balance scale

without VR < with VR
without VR = with VR

TRAINING WITH VR IS MORE EFFECTIVE THAN TRAINING WITHOUT VR

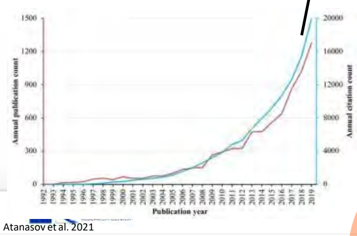
Multiple Sclerosis

Spatiotemporal gait parameters
Functional gait parameters

berg balance scale

without VR < with VR
without VR = with VR

Annual publication and citation count of virtual reality research in medicine



Atanasov et al. 2021

Cochrane Library

Cochrane Database of Systematic Reviews

Protocol published
Full Cochrane review submitted

De Keersmaecker E, Beckwée D, Denissen S, Nagels G, Jansen B, Swinnen E

Virtual reality for multiple sclerosis rehabilitation (Protocol)

To determine the effectiveness of virtual reality interventions compared with no intervention or an alternative intervention in people with MS on:

Cochrane

lower limb and gait function
balance and postural control
} Primary objective

upper limb function
cognitive function
fatigue
global motor function
activity limitation
participation restriction and quality of life
adverse events
} Secondary objective

Virtual reality versus no intervention in people with MS

Cochrane

10 studies (primary outcomes)
- 9 studies used non-immersive VR, commercially available gaming consoles
- 1 study used fully-immersive VR

Pooled results:

lower limb and gait function:	Timed up and Go (6 studies) MS Walking Scale – 12 (4 studies) Walking endurance (4 studies) gait speed (5 studies)
balance and postural control:	Berg Balance Scale (4 studies)

Virtual reality versus no intervention in people with MS

Cochrane

gait speed (5 studies)

Study or Subgroup	Experimental Mean	Experimental SD	Experimental Total	Control Mean	Control SD	Control Total	Weight	Std. mean difference IV, Fixed, 95% CI
Hoang 2016	2	4.58	23	-0.3	4.63	21	19.6%	0.49 [-0.11 , 1.09]
Nilsagård 2012	0.3	1.1	41	0	1.4	39	36.6%	0.24 [-0.20 , 0.68]
Novotna 2019	5.41	44.25	23	-5.91	34.86	16	17.2%	0.27 [-0.37 , 0.91]
Ozdogar 2020	2.6	1.9	20	-0.6	1.2	20	12.0%	1.97 [1.20 , 2.74]
Robinson 2015	11.9	28.04	20	-11.1	32.3	15	14.7%	0.75 [0.06 , 1.45]
Total (95% CI)			**127**			**111**	**100.0%**	**0.58 [0.31 , 0.84]**

Heterogeneity: Chi² = 16.15, df = 4 (P = 0.003); I² = 75%
Test for overall effect: Z = 4.24 (P < 0.0001)
Test for subgroup differences: Not applicable

Favours no intervention / Favours VR

Berg Balance Scale (4 studies)

more than 10 hours of therapy (2 studies) > less than 10 hours of therapy (2 studies)

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Virtual reality versus conventional therapy in people with MS

Cochrane

13 studies (primary outcomes)
- 11 studies used non-immersive VR, commercially available gaming consoles
- 2 studies used semi-immersive VR

Pooled results:

lower limb and gait function:
- Timed up and Go (4 studies)
- MS Walking Scale – 12 (4 studies)
- Walking endurance (4 studies)
- gait speed (8 studies)

balance and postural control:
- Berg Balance Scale (7 studies)
- Tinetti test (2 studies)
- Four Square Step Test (2 studies)

VUB – Human Robotics Research Center

Virtual reality versus conventional therapy in people with MS

Cochrane

Berg Balance Scale (7 studies)

Study or Subgroup	Experimental Mean	Experimental SD	Experimental Total	Control Mean	Control SD	Control Total	Weight	Mean difference IV, Fixed, 95% CI
Brichetto 2013	5	4.25	18	1	3.64	18	20.7%	4.00 [1.41 , 6.59]
Kalron 2016	1.1	4.2	15	1.3	5.2	15	12.1%	-0.20 [-3.58 , 3.18]
Khalil 2018	6.75	5.72	16	2.88	9.91	16	4.4%	3.87 [-1.74 , 9.48]
Lozano-Quilis 2014	2.333	8.01	8	0.2	8.11	5	2.7%	2.13 [-5.06 , 9.33]
Molhemi 2021	5.8	3.38	19	4.4	6.52	20	13.2%	1.40 [-1.84 , 4.64]
Peruzzi 2017	4	4.36	14	1	2.65	11	18.0%	3.00 [0.23 , 5.77]
Tollár 2019	6.1	3.52	14	3.9	2.25	14	28.9%	2.20 [0.01 , 4.39]
Total (95% CI)			**102**			**99**	**100.0%**	**2.39 [1.22 , 3.57]**

Heterogeneity: Chi² = 4.59, df = 6 (P = 0.60); I² = 0%
Test for overall effect: Z = 3.99 (P < 0.0001)
Test for subgroup differences: Not applicable

Favours conventional therapy / Favours VR

VUB – Human Robotics Research Center

Cochrane

small sample sizes, high risk of bias
considerable amount of heterogeneity, especially regarding outcome measures and interventions
meta-analyses and subgroup analysis based on limited number of studies

more research needed with more severely disabled people with MS

added value of an increased level of immersion is not clear due to the limited body of research using more immersive VR devices

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SYSTEMATIC REVIEWS PUBLISHED THE LAST YEARS

ORTHOPEDIC SURGERY
- ↑ functional recovery
- ↑ adherence
- ↓ anxiety
- ↓ pain
- …

Combalia et al. 2024, Mazurek et al. 2023, Ehioghae et al. 2024,...

MULTIPLE SCLEROSIS
- ↑ balance
- ↑ gait function
- ↓ fall risk
- ↓ fear of falling
- …

Castellano-Aguilera et al. 2022, Akkan et al. 2022, Calafiore et al. 2021, ...

STROKE
- ↑ balance
- ↑ functional ability
- ↑ physical performance
- ↑ strength
- …

Patsaki et al. 2022, Shen et al. 2022, Chen et al. 2022, ...

PARKINSON DISEASE
- ↑ balance
- ↑ gait speed
- ↑ motor skills
- ↓ fall risk
- …

Kashif et al. 2022, Wu et al. 2022, García-López et al. 2021,...

heterogenity between interventions
sometimes inconclusive findings
low to good quality with often small sample sizes
> or = conventional therapy

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CASUS
STATUS 5 DAYS POST-STROKE

- ROM: normal left and right
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- No sensory problems

Request for help: Mrs de Vries hopes that in the future she will no longer be dependent on others (for ADL and hygiene).

Would Virtual Reality applications be effective in this patient?

Contraindications?

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Is virtual reality beneficial for everybody?

How should such a virtual environment look like?

Does the virtual environment in which you practice has an influence?

Does it matter which device you use for the virtual reality?

?

Which elements should this virtual environment consist of?

…

RELATIVE MOTION BETWEEN YOURSELF AND YOUR ENVIRONMENT

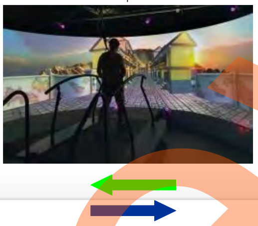
OPTIC FLOW

TASK-SPECIFIC, INTENSIVE AND REPETITIVE GAIT TRAINING

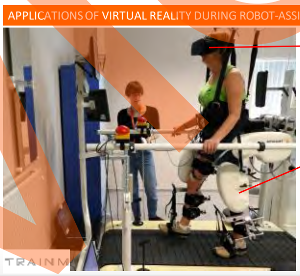
TREADMILL TRAINING

no optic flow

add optic flow



APPLICATIONS OF VIRTUAL REALITY DURING ROBOT-ASSISTED WALKING



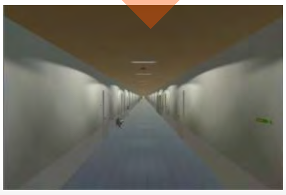
'Oculus Rift' – VR glasses (full immersive)

Lokomat – exoskeleton with a treadmill and bodyweight support

De Keersmaecker E, et al. The Effect of Optic Flow Speed on Active Participation During Robot-Assisted Treadmill Walking in Healthy Adults. IEEE Trans Neural Syst Rehabil Eng. 2020 Jan;28(1):221-227.

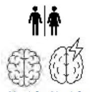
WALKING IN A VIRTUAL WORLD

EFFECT OF MANIPULATING THE OPTIC FLOW SPEED



De Keersmaecker et al. 2019

TYPE OF VIRTUAL REALITY & OPTIC FLOW SPEED

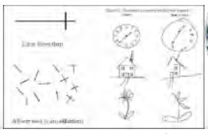


ST-parameters
Kinematics
Muscle activity
Questionaires

De Keersmaecker E, et al. Virtual reality-enhanced walking in people post-stroke: effect of optic flow speed and level of immersion on the gait biomechanics. J Neuroeng Rehabil. 2023 Sep 25;20(1):124.

VR FOR UNILATERAL VISUAL NEGLECT

Patients fail to report, respond or orient to meaningful stimuli presented on the affected side.



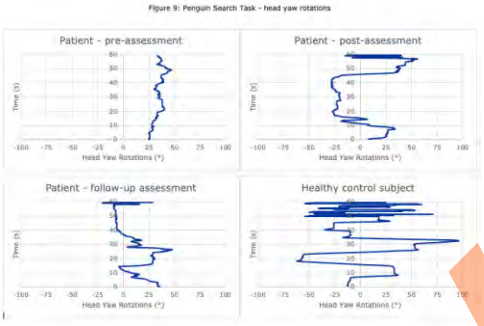
1) *Penguin Search*
2) *Smartphone Search*
3) *Apple Examination*
4) *Penguin Extinction*
5) *Grabbing Cubes*

VR FOR UNILATERAL VISUAL NEGLECT

Case study:

- 20 min training, 5 days
- Pre- and post-measurements with the BITC test (pen and paper test) + VR exercises
- head movements during VR exercises

Test item	Assessment		
	Pre	Post	Follow-up
Line Crossing (/36)	32	23	32
Letter Cancellation (/40)	38	33	25
Star Cancellation (/54)	27	40	30
Figure and Shape Copying (/4)	0	1	2
Line Bisection (/9)	0	0	5
Representational Drawing (/3)	2	2	2
Total (/146)	99	99	96



3 TOPICS

VIRTUAL REALITY

AUGMENTED REALITY

SENSOR BASED GAMING

AUGMENTED REALITY

FOR PATIENT

FOR THERAPIST

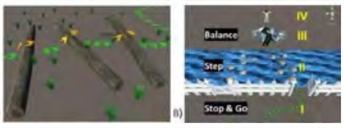
E. Swinnen
14-02-2024 | 52

AR FOR WALKING

- Projecting lines on the ground
- Virtual obstacles
- Mini-games (e.g. coloured round shape to catch)
- Combination with sensor-based Mocap to visualise the joints

CP children

Stroke



Al-Issa et al. 2012, Guinet et al. 2020, Held et al. 2020

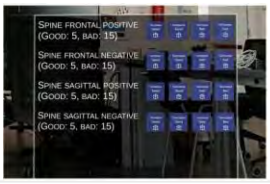
AR FOR UPPER/LOWER LIMB EXERCISES

- HMD or Laptop
- Combination with Mocap or SEmg
- Module for the physiotherapist to track the patient performance
- ADL activities (i.e. put a cup on a table)
- Shoulder rehabilitation, Stroke Parkinson, ...

Alamri et al. 2010, Aung et al. 2014, Sousa et al. 2016, Cavalcanti et al. 2018, Navarro et al. 2015

AR FOR POSTURAL EXERCISES

- Hololens collects data from Kinect and Balance Board while the patient performs a set of exercises/games
- Data can be visualized for the patient and/or physiotherapist in real time
- Game score, RoM, velocity, Center Of Pressure (CoP) and Center Of Mass (CoM)



Pezzera et al. 2020

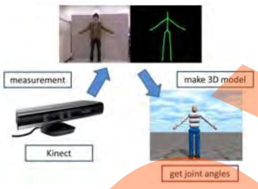
Examples of commercial available games

AR FOR JOINTS ROM EVALUATION

- First motion capture with Vicon

Figure 2: Overview of the system architecture.

- motion capture with Kinect
- Joint angles estimation by joint positions



Debarba et al. 2018, Kusaka et al. 2014

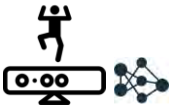
IMAGINE A SINGLE, PORTABLE PAIR OF GLASSES TO ASSESS HUMAN MOTION BY REAL-TIME VISUALIZATION OF GAIT PARAMETERS

Dra. Silvia Zaccardi

WHY?

Motion capture with markers is cumbersome

Motion capture without markers is not accurate



Goal is:
- To develop a **DL model** to perform motion capture sufficiently accurate **for clinical gait analysis**
- To obtain a light, modular DL architecture that it can easily be integrated in AR solutions with limited computational hardware

Other: biomechanical lessons and surgery guidance

3 TOPICS

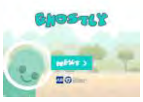
VIRTUAL REALITY

AUGMENTED REALITY

SENSOR BASED GAMING

GHOSTLY APP

SENSOR-BASED GAMING APP: MOVING AN AVATAR WITH MUSCLE CONTRACTIONS



DE LUCA FOUNDATION

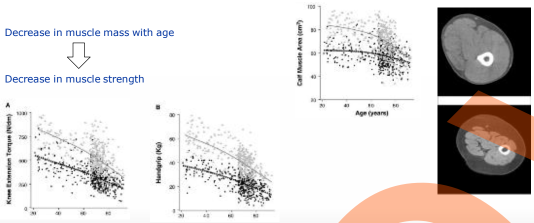
Phase I and II winner of the App development competition

OLDER ADULTS

Decrease in muscle mass with age

⇩

Decrease in muscle strength

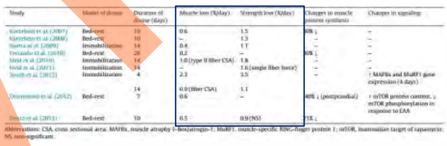


Lauretani et al. 2003

Roubenoff 2003

PHYSICAL INACTIVITY

Decrease in muscle mass and muscle strength



0.5%/day ➔ 150g muscle loss per day

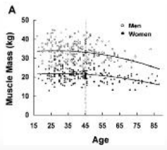
After 10 days ➔ 1.5 kg

Wall et al. 2013

PHYSICAL INACTIVITY

0.5%/day ➔ 150g muscle loss per day

After 10 days ➔ 1.5 kg



Janssen et al. 2000

TREATMENT OPPORTUNITIES

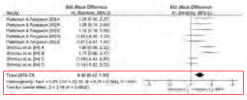
Dent et al. International Clinical Practice Guidelines for Sarcopenia (ICFSR): Screening, Diagnosis and Management. J Nutr Health Aging. 2018;22(10):1148-1161

BLOOD FLOW RESTRICTION

GHOSTLY

Partial occlusion of blood flow in working musculature during training

Beneficial effects already proven in older adults



Centner et al. 2019

VUB RERE REHABILITATION RESEARCH GROUP · VUB ETRO ELECTRONICS & INFORMATICS

GHOSTLY

- Gaming app
- Developed based on user-centered design principles
- Main character controlled through muscle contractions (EMG)
- Levels developed based on exercise guidelines

VUB RERE REHABILITATION RESEARCH GROUP · VUB ETRO ELECTRONICS & INFORMATICS

STUDY PROTOCOL

GHOSTLY

Feasibility of the Ghostly app as an **added training modality** for lower limb muscle strength in a hospitalized population

Population	Group	Intervention
Hospitalized older adults	EG1	Conventional therapy + Ghostly
	EG2	Conventional therapy + Ghostly + BFR
	CG	Conventional therapy + isometric exercises

PRIMARY OUTCOME MEASURE

UX

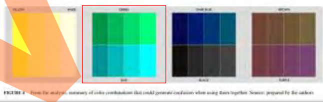
+ objective muscle outcomes

VUB RERE REHABILITATION RESEARCH GROUP · Drs. Ruben Debeuf · VUB ETRO ELECTRONICS & INFORMATICS

PRELIMINARY CHANGES

GHOSTLY

- Decline in color perception with older age
- Confusing color combinations: yellow/white, blue/green, dark blue/black and purple/dark red



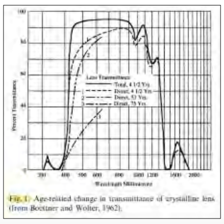


Fig. 1. Age-related change in transmittance of crystalline lens (from Boettner and Wolter, 1962).

Dodd et al. 2017

Delcampo-Carda t al. 2019

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PRELIMINARY CHANGES

GHOSTLY

- Reaction time and speed
- Different requirements for different populations

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There are many possibilities and opportunities for using VR/AR applications in neurological patients!

Promising results, but is the technology ready for optimal rehabilitation?

VUB BRUBOTICS HUMAN ROBOTICS RESEARCH CENTER


Het denken
onderwerpt zich niet.
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UNIVERSITEIT
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REHABILITATION RESEARCH GROUP

ROBOTICS FOR REHABILITATION

Prof. dr. Eva Swinnen

Master in Physiotherapy and Rehabilitation Science
PhD in robotic gait rehabilitation in neurological patients

Brussels Human Robotics Research Center (BRUBOTICS)
Center for Neurosciences (C4N)

I DECLARE THAT I HAVE NO CONFLICT OF INTEREST WITH RESPECT TO THE CONTENT OF THIS PRESENTATION.

Gait training/rehabilitation is different for different types of neurological patients and depends on the severity of the disorder / limitations of the patients

For example: Parkinson gait training versus Stroke gait rehabilitation

…

Overground training

Overground training with body weight support

Overground training with robot-assistance (exoskeleton devices)

Treadmill training

Treadmill training with body weight support

Treadmill training with robot-assistance (exoskeleton devices / end-effector devices)

CASUS

Mrs. De Vries is a 76-year-old retired woman who used to be a saleswoman. She is an active lady who loves walking with her dog, visiting her friends and dancing with her husband. On Tuesday, September 5, 2019, Mrs. de Vries had agreed to meet a friend at 10 am. Her husband had left early that morning for the local market. However, Mrs. de Vries did not show up and her friend became worried. During her lunch break (around noon) her daughter went to see her mother and found her lying on the ground in the kitchen. Around the same time, Mr. De Vries also returned home. Mrs De Vries lay unconscious on the floor and there was an unpleasant smell in the kitchen. The daughter immediately called an ambulance, after which Mrs. de Vries was taken to the nearest hospital. There she first went to the intensive care unit, after which a surgical thrombectomy was performed (left cerebral artery area). Subsequently, Mrs. de Vries was transferred to the stroke unit at the Neurology department.

CASUS

STATUS 5 DAYS POST STROKE

Could body weight supported and/or robot-assisted gait training be useful for this patient?
-now in the acute phase?
-later in the subacute or chronic phase?

- ROM: normal left and right
- Muscle strength
  - Right arm: proximal 2/5, distal 2/5
  - Right leg: global 2/5
- Gait pattern: patient needs firm continuous support from therapist (FAC 1)
- Motricity Index: Upper limb 39/100 ; Lower limb 37/100
- Berg Balance Scale: 6/56
- Trunk control test: 62/100
- Barthel Index: 46/100
- No spasticity
- No sensory problems

Request for help: Mrs de Vries hopes that in the future she will no longer be dependent on others (for ADL and hygiene)

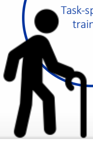
HOW CAN WE INCREASE THE EFFECT OF NEUROREHABILITATION?

- Task-specific training
- High intensity training with a high number of repetitions
- Goal-oriented training

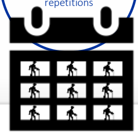
HOW CAN WE INCREASE THE EFFECT OF NEUROREHABILITATION?

APPLIED TO GAIT TRAINING

Task-specific training



High intensity training with a high number of repetitions



Goal-oriented training

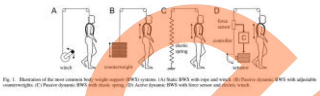
- ✓ Task specific
- ✓ High intensity
- ✓ Goal-oriented

DIFFERENT SYSTEMS FOR BWS TRAINING

Differences in suspension-system (1 point, 2 points,...)

Differences in harness (sizes, straps,...)

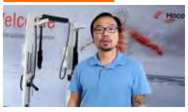
Differences in suspension type (static, passive, dynamic, ...)



BIODEX-SYSTEM

ZERO G SYSTEM

ANDAGO-SYSTEM



LITEGAIT-SYSTEM

BODY WEIGHT SUPPORTED GAIT TRAINING

Effectivity ?

Advantages:

↓ compensatory strategies (↑ symmetry)
↑ walking speed, ↑ safety and ↓ fear / risk of falling
Task-specific training with high number of repetitions (more steps)

Disadvantages: Labor intensive for therapist (amount of staff + low at the ground)
Sometimes not moveable
BWS 〉45 to 50% influence the walking pattern (toe-walking) and changes in thorax and pelvis biomechanics

- **Harness:** ↓ vertical acceleration (Aaslund 2008)
- **BWS:** ↓ acceleration in 3 directions (Aaslund 2008), ↓ inter-segmental coordination thorax-pelvis (Pintér 2006), ↓ amplitude muscle activity (Finch 1991, Swinnen 2014)

Optimal setting ? Often: 30 to 40% of the body weight at a low walking speed (0,1 tot 0,3 m/s) and increase gait speed, walking distance, duration, and reduce body weight support to 0%

EFFECTIVITY

STROKE

People after stroke who receive treadmill with or without BWS are not more likely to improve their ability to walk independently compared with people after stroke not receiving treadmill training, but walking speed and walking endurance may improve.

Specifically, stroke patients who are able to walk (but not people who are not able to walk) appear to benefit most from this type of intervention. This review found that improvements in walking endurance in people able to walk may have persisting beneficial effects.

44 TRIALS WITH 2658 PARTICIPANTS (UP TO JUNE 2013)

Mehrholz 2014

EFFECTIVITY

PARKINSON DISEASE

The use of treadmill training in patients with PD may improve clinically relevant gait parameters such as gait speed and stride length.

Comparing physiotherapy and treadmill training against other alternatives in the treatment of gait hypokinesia such as physiotherapy without treadmill training this type of therapy seems to be more beneficial in practice without increased risk. The gain seems small to moderate clinically relevant.

In practice when treadmill training is available this technology might be used in relatively yound and fit people with pd to improve gait speed as one specific parameter of gait hypokinesia.

18 TRIALS (633 PARTICIPANTS)

Mehrholz

EFFECTIVITY

MULTIPLE SCLEROSIS

Several studies indicate improvements in walking speed and maximum walking distance in individuals with MS after treadmill training with or without bodyweight support. Furthermore, improvements in stride length, double support time and EDSS are also reported. However, there is no evidence as to which treadmill training gives the best results.

8 TRIALS (161 PARTICIPANTS)

Swinnen 2014

HIBBOT

Handsfree walking, Counterweight, Reverse brake, Stabilizing Pelvic instability, Stability compass, Fall prevention

CASUS

STATUS 5 DAYS POST STROKE

Could body weight supported and/or robot-assisted gait training be useful for this patient?
-now in the acute phase?
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- ROM: normal left and right
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- No sensory problems

Request for help: Mrs de Vries hopes that in the future she will no longer be dependent on others (for ADL and hygiene).

Treadmill based exoskeletons | End-effectors | Mobile exoskeletons

Treadmill based exoskeletons

Lokomat (Hocoma)
Reo-Ambulator
LOPES
ALEX
Altacro
...

End-effectors

G-EO system (Reha Technology)
Gait trainer GT
LokoHelp
...

Wearable exoskeletons

Ekso GT / NR (Ekso Bionics)
Rewalk
Indego
MIRAD
...

EXAMPLE TREADMILL BASED EXOSKELETON: LOKOMAT (HOCOMA AG SWITZERLAND)

4 actuated joint (hip and knee), passive elastic strips feet, pre-programmed gait pattern

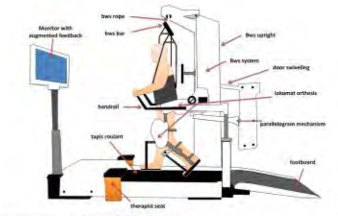
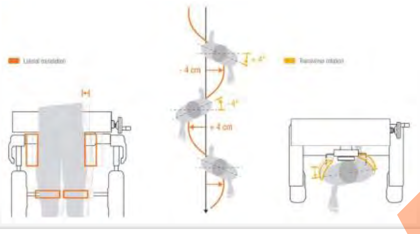


Fig. 1 A typical stationary exoskeleton-type device (i.e. Lokomat) *Calabro et al. 2016*

Lokomat PRO – Free D module pelvis



EXAMPLE END-EFFECTOR: G-EO SYSTEM (REHA TECHNOLOGY[®])

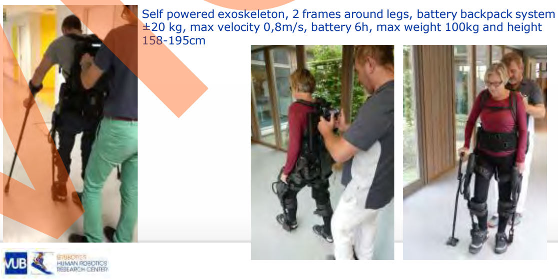
Programmable footplates move the feet in the sagittal plane
walking + stairs + partial movements, active / active-passive mode

Fig. 2 Programmable foot end-effector device. Gait Trainer

Calabro et al. 2016

EXAMPLE WEARABLE EXOSKELETON: EKSO NR (EKSOBIONICS)

Self powered exoskeleton, 2 frames around legs, battery backpack system
±20 kg, max velocity 0,8m/s, battery 6h, max weight 100kg and height 158-195cm



EXAMPLE OF WEARABLE EXOSKELETON: MYOSUIT (MYOSWISS)

active orthosis that enables intensive training of strength, endurance, and balance activities in any environment

At home or outdoors

The Myosuit provides assistance as you move, amplifying your strength and endurance, much like an e-bike augments your power when pedaling

Supports the hips and knees simultaneously

Light

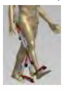
E. Swinnen
23

BRUBOTICS LOWER LIMB EXOSKELETON PROJECTS IN REHABILITATION

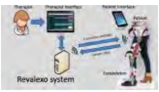
ALTACRO PROJECT (2008) → MIRAD PROJECT (2013) → REVALEXO PROJECT (10/2023)

Biomechanical outcomes:
EMG
Kinematics
…

MIRAD PROJECT (2013)



Biomechanical outcomes:
EMG
Kinematics
Energyconsumption
+
Acceptation/user-satisfaction/intrinsic motivation/…



REVALEXO PROJECT (10/2023)

A wearable lower-limb exoskeleton that assists activities of daily living and enables data-driven remote rehabilitation

PERsona-CEntered Participatory Technology (PERCEPT) approach for co-creation:*
involves applying personas with target users during the exploration, design and evaluation steps
+
user testing: biomechanical outcomes + user-experiences

SBO projects with a primary economic finality aimed at the transfer to existing companies

E. Swinnen

ROBOT-ASSISTED GAIT THERAPY

Advantages: Less physical assistance from therapist
More repetitions, longer training sessions
Improving skills in patients with severe disabilites
Improve quality of the movement
Improve motivation

Disadvantages: High costs of the equipment
Transportability of the systems
Predescribed (gait) pattern, limited degrees of freedom

Between all devices: large differences

Effectivity ?

"…it may be the time to change the research question from

"Is robotic-assisted training effective …?"

to

"Who may benefit from robotic training?"

Morone et al., Aurich et al., Cochrane Reviews, …. and others

EFFECTIVITY

STROKE

People who receive RAGT in combination with physiotherapy after stroke are more likely to achieve independent walking than people who receive gait training without these devices.

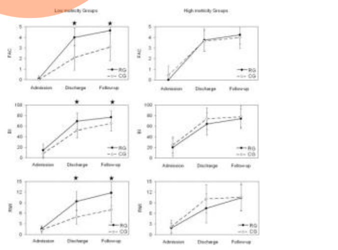
Specifically, people in the first three months after stroke and those who are not able to walk seem to benefit most from this type of intervention.

Mehrholz 2021, Swinnen 2014, Morone et al. 2011

RCT (n=48): lower and higher motricity groups

Higher efficacy of the combination of robotic therapy and conventional therapy versus conventional therapy alone

Mean and SD of the recorded scale scores.



Giovanni Morone et al. Stroke. 2012;43:1140-1142

EFFECTIVITY

MULTIPLE SCLEROSIS

RAGT in PwMS has a beneficial effect on walking speed, maximum walking distance, EDSS score, spasticity, muscle strength, balance and quality of life. There is in no ambiguous evidence that RAGT is more effective compared to other rehabilitation methods.

Some studies suggested that superior clinical effects of RAGT compared to conventional treatment are present in more severely affected people with multiple sclerosis, while more equal effects are found for moderately disabled patients who still have substantial overground walking abilities

Bowman 2021, Salvatore 2021, Swinnen 2012, Lamers 2018, Feys & Swinnen 2021

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www.reha-stim.com

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Table 2 Overview of studies investigating robot-assisted gait training (RAGT)

Publication	N	Training (RAGT)	EDSS (RAGT)	Robotic device	Type	Significant treatment effects
Lo et al. [28] NNR—pilot RCT BWSTT and RAGT	13 (crossover design)	2×40'/week for 3 weeks, 6 sessions	4.9	LOKOMAT	Exoskeleton	Walking speed (timed 25 ft walk), walking capacity (6-min walk distance), percentage of double support time, severity of MS (EDSS)
Pompa et al. [30] MSJ	13 (crossover design)	idem Lo et al. [28]	idem Lo et al. [28]	idem Lo et al. [28]	idem Lo et al. [28]	Quality of life
Beer et al. [31] MS—RCT RAGT versus CWT	35 (19 RAGT)	5×30' walking time/week for 3 weeks, 15 sessions	6.5	Lokomat	Exoskeleton	Walking speed, distance and knee extensor strength
Vaney et al. [32] NNR—RCT RAGT versus CWT	49 (26 RAGT)	3×30'/week for 3 weeks, 9 sessions	5.9	Lokomat	Exoskeleton	
Schwartz et al. [33] MSJ RCT RAGT versus CWT	32 (15 RAGT)	2–3×30' walking time/week for 4 weeks, 12 sessions	6.3	Lokomat	Exoskeleton	Functional mobility, functional independence measure, overall disability
Ruiz et al. [34] JNPT	7 (immediate/delayed treatment group)	2×20'/w for 2 months, 16 sessions	5	Lokomat	Exoskeleton	Walking distance, functional balance

Continued


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Table 2 Overview of studies investigating robot-assisted gait training (RAGT)—cont'd

Publication	N	Training (RAGT)	EDSS (RAGT)	Robotic device	Type	Significant treatment effects
Gandolfi et al. [35] Front Hum Neurosci—RCT RAGT versus balance training	22 (12 RAGT)	2×50'/week for 6 weeks, 12 sessions	4	Gait trainer GTI	End-effector device	Static and dynamic balance, balance confidence
Straudi et al. [37] NR—pilot RCT RAGT versus CT	16 (8 RAGT)	2×30' walking time/week for 6 weeks, 12 sessions	5.8	Lokomat	Exoskeleton	Walking speed, distance, gait pattern, and kinematics
Straudi et al. [37] MS—RCT RAGT versus CT	52 (27 RAGT)	2×30' walking time/week for 6 weeks, 12 sessions	6.4	Lokomat	Exoskeleton	Walking distance, balance, quality of life
Pompa et al. [33] MSJ—pilot RCT comparing RAGT with CWT	43 (21 RAGT)	3×40'/week for 4 weeks, 12 sessions	6.2	Gait trainer GTI	End-effector device	Walking speed, ability, overall disability, fatigue, overall mobility and activities of daily living, lower limb spasticity

RCT, randomized controlled trial; RAGT, robot-assisted gait training; EDSS, expanded disability status scale; CWT, conventional walking training; CT, conventional training.

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MULTIPLE SCLEROSIS JOURNAL MSJ

Clinical Commentary

Powered exoskeletons for walking in multiple sclerosis

Peter Feys and Eva Swinnen

case report with EDSS 8 using a powered exoskeleton during 15 weeks interestingly showed important improvements in psychological and social outcomes, as well as increased muscle strength leading to improved transfer ability. Previous studies have also indicated improvements in sitting, standing and walking postures, or endurance in gait after use of powered exoskeletons as ReWalk and Keeogo.[7,8] It is concluded that these new technologies are worth exploring across the disability spectrum on multidimensional effects.

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EFFECTIVITY

SPINAL CORD INJURY

Robot-assisted gait training improves mobility-related outcomes (e.g. walking speed, distance, muscle strength, RoM) to a greater degree than conventional overground training for patients with incomplete spinal cord injury, particularly during the acute stage.

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Alashram 2021, Nam 2017, Mehrholz 2012, Swinnen 2010

EFFECTIVITY

PARKINSON DISEASE

Robot-assisted gait training gives better results than conventional interventions for certain motor aspects (stride length, walking speed and balance), but is not always superior to control interventions in general.

There is evidence, but from a limited number of studies, that robot-assisted gait training is useful for improving freezing of the gait and balance.

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Picelli 2021, Alwardat 2018, 2019,

CASUS

STATUS 5 DAYS POST STROKE

Could body weight supported and/or robot-assisted gait training be useful for this patient?
-now in the acute phase?
-later in the more subacute or chronic phase

Which type of robot would you use?
What will be your therapyplan if there is a positive evolution of the patient?
Contraindications?

- ROM: normal left and right
- Muscle strength
  - Right arm: proximal 2/5, distal 2/5
  - Right leg: global 2/5
- Gait pattern: patient needs firm continuous support from therapist (FAC 1)
- Motricity Index: Upper limb 39/100 ; Lower limb 37/100
- Berg Balance Scale: 6/56
- Trunk control test: 62/100
- Barthel Index: 46/100
- No spasticity
- No sensory problems

Request for help: Mrs de Vries hopes that in the future she will no longer be dependent on others (for ADL and hygiene).

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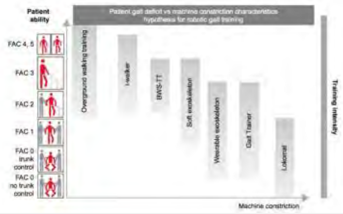
NEED FOR PRACTICAL GUIDELINES



Morone et al 2017

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ENERGY CONSUMPTION

FAC 3–4

- Use BWS system instead of a robotic system to challenge the cardiorespiratory system during walking
- Use a robotic system to extend training time (> 20 minutes)

FAC ≤ 2

- Robotic systems can be used for aerobic exercise, but training intensity is low
- Keep in mind that lowering robot assistance does not increase the training intensity of robot training

Lefeber et al. 2017, 2018, 2020, 2021

Upper Extremity	Grounded Exoskeleton	Grounded End-Effector	Wearable Exoskeleton
Development Status	Established	Established	Emerging
Technology Reviews	**Upper Limb:** Loureiro 2011, Maciejasz 2014, Sheng 2016 (bilateral) | **Hand:** Lum 2012, Bos 2016		
Clinical Evidence	**Grounded:** Klamroth, 2014 | **End-Effector:** Lo 2010 | **Both:** Kwakkel 2008, Mehrholz 2015, Veerbeek 2017 **Hand:** Balasubramanian 2010, Lambercy 2011		

EXAMPLES STATIONARY EXOSKELETON

ARMEO POWER (HOCOMA)

For patients with severe impairements

"assisted as needed" during movement

6 Degrees of Freedom (1D, 2D and 3D movements)

Feedback (games, augmented performance)

Objective measurements

EXAMPLE STATIONARY END-EFFECTOR

AMADEO (TYROMOTION)

Robot and sensor-based rehabilitation for hand and fingers

Adults and Children

Passive, assistive en active mode

Feedback

EXAMPLE MOBILE EXOSKELETON

RESEARCH-EXOSKELETONS

Hong Kong PolyU Robot exoskeleton with integrated FES (functional electrical stimulation)

Target group: stroke

EVIDENCE?

Cochrane systematic review Mehrholz et al. (Update 2018): **Electromechanical and robot-assisted arm training for improving activities of daily living, arm function, and arm muscle strength after stroke**

- People who receive electromechanical and robot-assisted arm training after stroke might improve their activities of daily living, arm function, and arm muscle strength.
- However, the results must be interpreted with caution although the quality of the evidence was high, because there were variations between the trials in: the intensity, duration, and amount of training; type of treatment; participant characteristics; and measurements used.

POTENTIAL FOR ACURATE MEASUREMENTS

Measurements of the status of the patient

Measurements of the progression of the therapy

Real-time feedback for the therapist and/or patient

Iosa et al. 2016, Keller et al. 2015

In the development of efficacious RAGT approaches or novel robotic devices, it is interesting to also consider patients' and therapists' perspectives, such as **motivation, expectations** or **usability**, with respect to RAGT

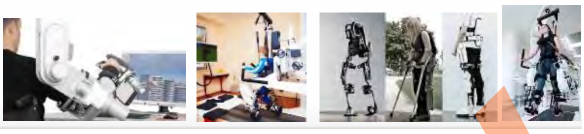
Related to treatment outcome!

Motivation, expectations, and usability of a driven gait orthosis in stroke patients and their therapists

Eva Swinnen, Nina Lefeber, Ward Willaert, Fallon De Neef, Lyn Bruyndonckx, Annemie Spooren, Marc Michielsen, Tine Ramon & Eric Kerckhofs

To cite this article: Eva Swinnen, Nina Lefeber, Ward Willaert, Fallon De Neef, Lyn Bruyndonckx, Annemie Spooren, Marc Michielsen, Tine Ramon & Eric Kerckhofs (2016): Motivation, expectations, and usability of a driven gait orthosis in stroke patients and their therapists, Topics in Stroke Rehabilitation, DOI: 10.1080/10749357.2016.1266750

To link to this article: http://dx.doi.org/10.1080/10749357.2016.1266750

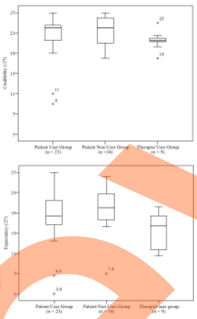


RESULTS CREDIBILITY AND EXPECTANCY

In general, stroke patients with and without Lokomat experience and their therapists reasonably believed that Lokomat training could improve gait functioning

No significant differences in credibility and expectancy were found between the stroke user, stroke non-user and therapist user group.

→ training in the system does not increase or decrease the expectations or credibility



RESULTS USABILITY

Therapists were moderately satisfied with the usability of the Lokomat

They thought:

- -it is somewhat useful, but also time consuming
- -using it requires some effort and is not that simple
- -it is quite easy to remember how to use it and it is usable without written instructions

→ Reducing donning times could be an important aspect to address by engineers!

WHAT ARE NEW TRENDS AND EVOLUTIONS?

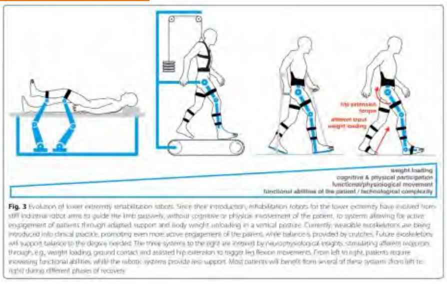
Stationar to mobale systems

Soft exoskeletons

Combinations of technologieën

Telerehabilitation

STATIONAR TO MOBILE SYSTEMEN

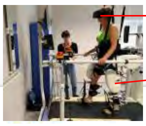


SOFT EXOSKELETONS

COMBINATIONS OF TECHNOLOGY

tDCS + robotic training

BRAIN-exoskeletons



'Oculus Rift' – fully immersive VR headset

Lokomat – exoskeleton for gait rehabilitation

TELEREHABILITATION

Telerehabilitation

vb. Phones, audio-video conferences, ...

External sensors (real-time movements/postures of patients – feedback by therapist)

vb. mobile applications (ipad, iphone, smartphone, tablet-based,...)

There are many possibilities and opportunities for using robotics during rehabilitatation!

Promising results, but is the technology ready for optimal rehabilitation?

TAKE HOME MESSAGES !

Using technology to practice specific repetitive body movements has promising results.

Therapists should be aware of the many possibilities but also the limitations of technology applications.

Rehabilitation with technology applications is not a stand-alone therapy, but should be implemented in the overall rehabilitation plan.

Research should further focus on specific conditions, severity of disorders, type and settings of devices,...

Specific guidelines for implementing technological applications should be further developed for clinical practice.

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4 Design and control of rehabilitation robots (Prof. Dr. Tom Verstraten)

: Design and control of rehabilitation robots

4.1 Introduction:

4.1.1 Types of rehabilitation robots for the lower extremity

4.1.2 History

4.2 Building a rehabilitation exoskeleton

4.2.1 Overview design challenges

4.2.1.1 Wearability

4.2.1.2 Kinematic compatibility

4.2.1.3 Physical interfaces

4.2.1.4 Usability

4.3 Control of rehabilitation robots

4.4 What are we working on right now?

4.5 Additional information, slides, articles

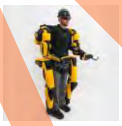
DESIGN AND CONTROL OF REHABILITATION ROBOTS

Prof. dr. ir. Tom Verstraten

Rehabilitation robots

Exoskeleton

Robotic exoskeletons


Guardian XO (Sarcos, US)


ReWalk (ReWalk Robotics, IL)


Lokomat (Hocoma, CH)


Mate-XB (Comau)

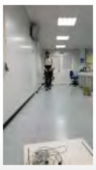

ALEx (KineteK, IT)

VUB exoskeletons

Mirad project: Lower limb exoskeleton for partial assistance of gait

Altacro project: Development and clinical testing of a step rehabilitation robot

Biomot project: Lower limb exoskeleton for full assistance of gait



The first exoskeleton

Hardiman (1965-1971)

Building a rehabilitation exoskeleton


Mechanical design


Control

Design challenges: overview

- **Wearability**
  - Mass
  - Size
  - Fit to user
  - Compatibility with clothes
  - Distal mass
- **Kinematic compatibility**
  - Degrees of freedom
  - Misalignment
- **Physical interfaces**
  - Comfort
  - Effective at transmitting forces
- **Usability**
  - Energetic autonomy
  - Washability
  - Easy donning/doffing
  - Intuitive to use

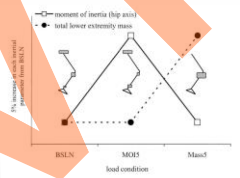
Key problem 1: mass and size

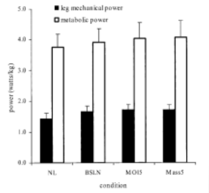
Some examples

Key problem 1: mass and size

Distal mass

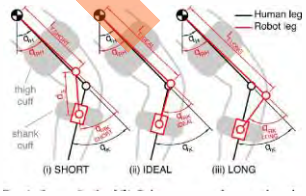
Royer and Martin (2005). *Manipulations of Leg Mass and Moment of Inertia: Effects on Energy Cost of Walking*. Medicine & Science in Sports & Exercise.





Key problem 2: Kinematic compatibility

Misalignment



Consequences:

- Delivered torque different from expected
- Sliding of exoskeleton interfaces
- Undesired interaction forces

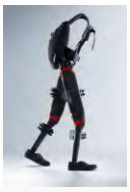
In general: cause for discomfort

Key problem 3: physical interfaces

Langlois et al. (2018). *Design and development of customized physical interfaces to reduce relative motion between the user and a powered ankle foot exoskeleton*. BioRob 2018.

Mechanical design
Key elements


Actuators


Exoskeleton structure


Physical interfaces

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Design challenges: overview

- **Wearability**
  - Mass
  - Size
  - Fit to user
  - Compatibility with clothes
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  - Degrees of freedom
  - Misalignment
- **Physical interfaces**
  - Comfort
  - Effective at transmitting forces
- **Usability**
  - Energetic autonomy
  - Washability
  - Easy donning/doffing
  - Intuitive to use

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Actuation
Why is it so difficult?


250 Nm (peak)

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Actuation
Why is it so difficult?

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Actuation
Skeletal muscle vs. engineered actuators


Skeletal muscle
Low power density (≈0.04W/g)
Low efficiency (≈ 25%)
High torques (≈50 Nm)


Electric motor
High power density (≈0.5W/g)
High maximum efficiency (≈ 90%)
Low torques (≈0.2 Nm)


Gearboxes
are needed to bridge the gap in motor torque,
but increase losses (typical efficiencies: 60-85%)

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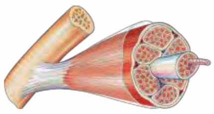
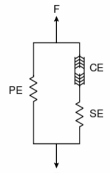
Actuation
From skeletal muscle to engineered actuators


Skeletal muscle



Hill muscle model


Series Elastic Actuator

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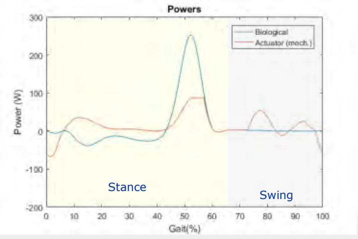
Actuation
Series Elastic Actuator (+ parallel spring)



Verstraten et al. (2017) *Optimizing the Power and Energy Consumption of Powered Prosthetic Ankles with Series and Parallel Elasticity.* Mechanism and Machine Theory, 116, 419-432.

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Actuation
Elastic actuation

21

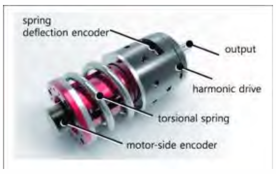
Actuation
Elastic actuation

22

Actuation
Series Elastic Actuator

Advantages:
- Energy-efficient
- Smaller motor/gearbox
- Inherently safe
- Eases donning/doffing
- Cheap torque measurement

Disadvantages:
- Mechanical complexity
- Difficult to control



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Actuation
Series Elastic Actuator


Symbitron
(TU Delft, NL)


BioMot
(VUB, BE)


Stanford ankle exoskeleton
(Stanford, US)

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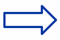
Actuation
Remote actuation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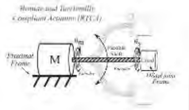
Actuation
Remote actuation

Advantages:
- Low distal mass
- Inherent compliance

Disadvantages:
- Higher total mass
- Additional transmission losses
- Limited in torque transmission capability
- Mechanically complex



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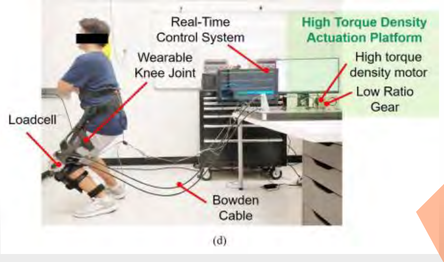
Actuation
Remote actuation



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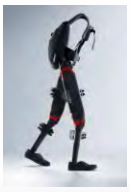
Mechanical design
Key elements

Actuators



Exoskeleton structure

Physical interfaces

28

Design challenges: overview

- **Wearability**
  - Mass
  - Size
  - Fit to user
  - Compatibility with clothes
  - Distal mass
- **Kinematic compatibility**
  - Degrees of freedom
  - Misalignment
- **Physical interfaces**
  - Comfort
  - Effective at transmitting forces
- **Usability**
  - Energetic autonomy
  - Washability
  - Easy donning/doffing
  - Intuitive to use

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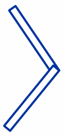
Exoskeleton structure
Connections between parts



Fixed

Active joint

Freely rotating

Spring-loaded

Passive joint

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Exoskeleton structure
Addressing pelvic movement: additional active DOFs

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Exoskeleton structure
Addressing misalignment: additional passive DOFs



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Exoskeleton structure
Exosuits

Myosuit (MyoSwiss, CH)

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Exoskeleton structure
Exosuits

Advantages:
- Low mass
- Very compact/wearable
- Easy to don/doff

Disadvantages:
- Forces difficult to control
- Interfaces slide along skin
- Medium-low assistance
- Additional load on skeletal joints

Myosuit (MyoSwiss, CH)

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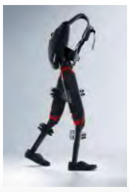
Mechanical design
Key elements

Actuators



Exoskeleton structure

Physical interfaces

35

Design challenges: overview

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Why is it so difficult?


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Customized interface

ir. Kevin Langlois

Langlois et al. (2018). *Design and development of customized physical interfaces to reduce relative motion between the user and a powered ankle foot exoskeleton.* BioRob 2018.

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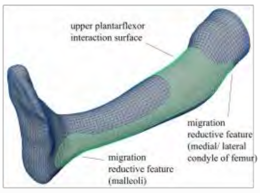
Customized interface

ir. Kevin Langlois



Langlois et al. (2018). *Design and development of customized physical interfaces to reduce relative motion between the user and a powered ankle foot exoskeleton.* BioRob 2018.

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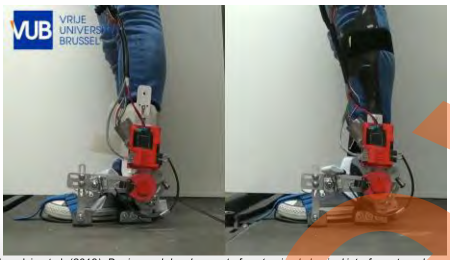
Commercial vs. customized interfaces

ir. Kevin Langlois



Langlois et al. (2018). *Design and development of customized physical interfaces to reduce relative motion between the user and a powered ankle foot exoskeleton.* BioRob 2018.

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Soft inflatable active interfaces

ir. Kevin Langlois

Langlois et al. (2020). *A Soft Robotic Cuff and the Effects of Strapping Pressure on Interface Dynamics and Perceived Comfort.* IEEE Transactions on Medical Robotics and Bionic.

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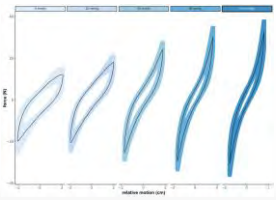
Soft inflatable active interfaces

ir. Kevin Langlois



Langlois et al. (2021). *A Soft Robotic Cuff and the Effects of Strapping Pressure on Interface Dynamics and Perceived Comfort.* IEEE Transactions on Medical Robotics and Bionics.

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Building a rehabilitation robot

Mechanical design

Control

Control of rehabilitation robots

Two main strategies:

Assistive strategies: Help patients to move their weakened limbs in desired patterns

Challenge-based strategies: make movement tasks more difficult or challenging

Marchal-Crespo and Reinkensmeyer (2009). *Review of control strategies for robotic movement training after neurologic injury*. Journal of NeuroEngineering and Rehabilitation.

Assistive controllers

Impedance-based control

Underlying idea: "Assistance as needed"

- when patient moves along desired trajectory, the robot should not intervene
- if patient deviates from desired trajectory, the robot should create a restoring force

What does the controller need to do?

⇒ Trajectory should not be strictly imposed (inherent variability of movements)

⇒ Assistive forces should increase as participant deviates from desired trajectory

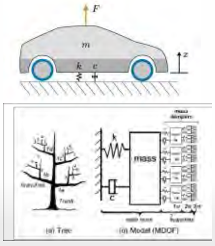
Solution: Generate assistive force using an appropriately designed mechanical impedance.

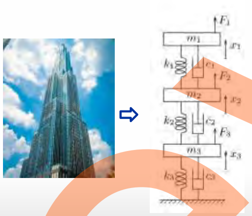
Marchal-Crespo and Reinkensmeyer (2009). *Review of control strategies for robotic movement training after neurologic injury*. Journal of NeuroEngineering and Rehabilitation.

Assistive controllers

Impedance-based control

To a mechanical engineer, everything is equivalent to springs, masses and dampers



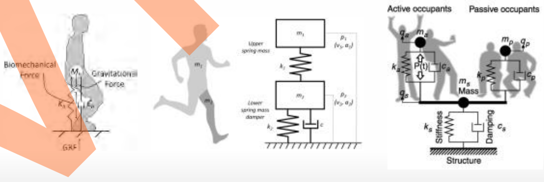


Assistive controllers

Impedance-based control

To a mechanical engineer, everything is equivalent to springs, masses and dampers

Even people

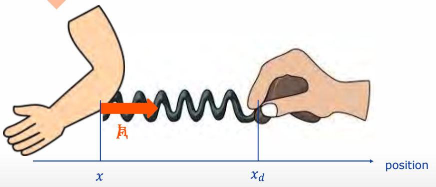


Assistive controllers

Impedance-based control

First controllers: proportional position feedback

$$F = k(x - x_d)$$



Marchal-Crespo and Reinkensmeyer (2009). *Review of control strategies for robotic movement training after neurologic injury*. Journal of NeuroEngineering and Rehabilitation.

Assistive controllers

Impedance-based control

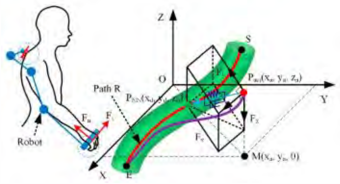
More recent controllers: Mechanical impedance

Marchal-Crespo and Reinkensmeyer (2009). *Review of control strategies for robotic movement training after neurologic injury*. Journal of NeuroEngineering and Rehabilitation.

Assistive controllers
Impedance-based control

Possible additions:

- Deadband
- Virtual channel
- Virtual moving wall



Marchal-Crespo and Reinkensmeyer (2009). *Review of control strategies for robotic movement training after neurologic injury*. Journal of NeuroEngineering and Rehabilitation.

Assistive controllers
Impedance-based control

How to set the stiffness (assistive force)?

Too compliant: patient is insufficiently supported ⟺ **Too stiff**: robot is doing all the work to move patient's limb(s)

⇒ The robot must calculate an **appropriate amount of force** to cancel effects of increased tone, weakness, or lack of coordinated control.

⇒ However, these vary widely between participants.

⇒ Need for **adaptive or learning-based controllers**:

"Performance-based adaptation"
"Assist-as-needed"
"Patient-cooperative control"

Assistive controllers
Performance-based adaptation

Concept: adapt control parameters based on measurement

Typical control law: $P_{i+1} = fP_i - ge_i$

Which control parameters P_i?

- Stiffness of impedance control
- Timing of trajectory
- Desired velocity
- Deadband
- …

Which performance error e_i?

- Ability to initiate movement
- Ability to reach a target
- Level of participation
- …

Marchal-Crespo and Reinkensmeyer (2009). *Review of control strategies for robotic movement training after neurologic injury*. Journal of NeuroEngineering and Rehabilitation.

Assistive controllers
Impedance-based control

How to determine the required trajectory?

- Normative movements (most common strategy)
  - What is "normative"?
- Pre-recorded trajectories from unimpaired volunteers
- Pre-recorded trajectories during therapist-guided assistance
- Replication of movement of unimpaired limb
- …

Adaptive strategies can also be applied to these trajectories.

Assistive controllers
EMG-based assistance

Idea: use sEMG signals from selected muscles as an indicator of effort/intention.

Two main implementations:

- Threshold-based
- Proportional myoelectric control (video on right)

Marchal-Crespo and Reinkensmeyer (2009). *Review of control strategies for robotic movement training after neurologic injury*. Journal of NeuroEngineering and Rehabilitation.

Assistive controllers
EMG-based assistance

Limitations of sEMG methods:

- sensitive to many factors
  - electrode placement
  - interference from neighboring muscles
  - skin properties (e.g. sweat on the skin, blood circulation)
- dependent on the overall neurologic condition of the individual
- EMG parameters need to be calibrated for every individual and recalibrated for each session.
- Abnormal, uncoordinated muscle activation patterns could lead to undesired robot movement.

Marchal-Crespo and Reinkensmeyer (2009). *Review of control strategies for robotic movement training after neurologic injury*. Journal of NeuroEngineering and Rehabilitation.

What are we working on right now?

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Exoskeleton for telerehabilitation

fwo

RevalExo

60

Integration of flexible sensors in interfaces

61

New control strategies

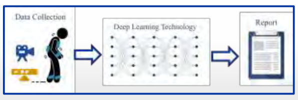
62

AI and musculoskeletal simulation

Human-in-the-loop optimization

Musculoskeletal modelling

Multimodal intention prediction algorithms



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Cybathlon

We are still looking for:
- Team members
- Person with amputation (contestant)

Interested?
Contact
Louis.Flynn@vub.be

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VUB BRUBOTICS HUMAN ROBOTICS RESEARCH CENTER

Let’s connect!

Tom Verstraten

ProfTomRobotics

Prof. Tom

www.brubotics.eu

5 Mobile Health (Dr. Marc Schiltz)

: Mobile Health

5.1 Introduction

5.2 Benefits

5.3 Exploring mHealth applications

5.3.1 Subtypes

5.3.2 Applications

5.3.3 Technology tools

5.3.4 Challenges and considerations

5.4 Telerehab in Belgium

5.4.1 Current state of affairs

5.4.2 MOVEUP.CARE

5.4.3 Beyond the trial

5.5 Additional information, slides, articles

VRIJE UNIVERSITEIT BRUSSEL | Universitair Ziekenhuis Brussel

MOBILE HEALTH

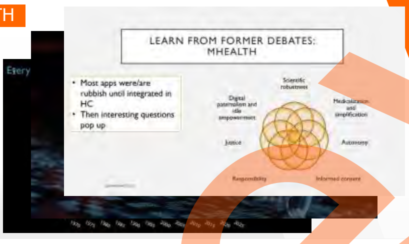
Marc Schiltz MD MBA

WELCOME AND INTRODUCTIONS

VRIJE UNIVERSITEIT BRUSSEL | Universitair Ziekenhuis Brussel

MOBILE HEALTH

Marc Schiltz MD MBA



INTRODUCTION

What is Mobile Health (mHealth)?

* Definition and scope:

- WHO Classification of Digital Health Interventions v 1.0
  - should be used in tandem with the of list Health System Challenges (HSC)

* Historical context and recent trends

* Different types of mHealth tools (apps, wearables, etc.)

INTRODUCTION

What is Mobile Health (mHealth)? Definition and scope: WHO 2016

- "mHealth": use of mobile wireless technologies for public health
- "digital health": broad umbrella term encompassing eHealth as well as developing areas such as the use of advanced computing sciences
- 2016: Digital technologies, such as mobile wireless technologies, have the potential to revolutionize how populations interact with national health services.
- Digital health and specifically mHealth have been shown:
  - improve quality and coverage of care
  - increase access to health information, services and skills
  - promote positive changes in health behaviours to prevent the onset of acute and chronic diseases

INTRODUCTION

What is Mobile Health (mHealth)? Definition and scope: WHO 2016

Istepanian RSH. Mobile Health (m-Health) in Retrospect: The Known Unknowns. *IJERPH*. 2022;19(7):3747. doi:10.3390/ijerph19073747

- "mHealth": mobile computing, medical sensor and communications technologies for healthcare
  - **Mobility:** various modalities of mobility that aimed to improve healthcare access, increased efficiency, and potential cost reductions. – context of smart phone Apps
  - **Monetary and Markets**: created unprecedented markets & business ecosystems on a global scale
  - **Medical Evidence** : some have proven to be clinically effective and beneficial, many remain debatable with no clear evidence

INTRODUCTION

What is Mobile Health (mHealth)? Definition and scope: WHO 2016

Istepanian RSH. Mobile Health (m-Health) in Retrospect: The Known Unknowns. *IJERPH*. 2022;19(7):3747. doi:10.3390/ijerph19073747

Figure 2. The evolution and key milestones of mobile health (2003–2021). (Adapted with permission from [1] 2017 Hoboken, NJ, USA: John Wiley & Sons).

INTRODUCTION

What is Mobile Health (mHealth)? Definition and scope: WHO 2016

" in spite of potentially wide applicability" … "challenging to assess, scale up and integrate such solutions"

- multiplicity of pilot projects with no clear plan or process for scale
- lack of interconnectedness between individual applications, and of integration with existing national eHealth strategies and health information architectures
- absence of standards and tools for the comparative assessment of functionality, scalability comparative value of fast-evolving digital health solutions, resulting in a lack of evidence to articulate normative guidance
- lack of a multisectoral approach within government
- Lack of engagement between ministries health & f information &communication technologies, & operators and the private sector

INTRODUCTION

What is Mobile Health (mHealth)? Definition and scope: WHO 2016

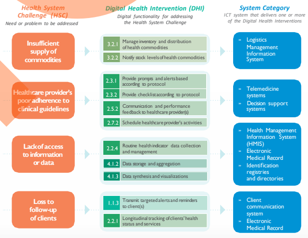
Potential for major role in:

- increasing access to quality health services.
- increasing access to sexual and reproductive health services; reducing maternal, child and neonatal mortality
- reducing premature mortality from noncommunicable diseases and noncommunicable disease comorbidities
- increasing global health security
- increasing the safety and quality of care
- increasing patient, family, and community engagement

INTRODUCTION

What is Mobile Health (mHealth)?

figure 1. Linkages across Health System Challenges, Digital Health Interventions, and System Categories



INTRODUCTION

What is Mobile Health (mHealth)?

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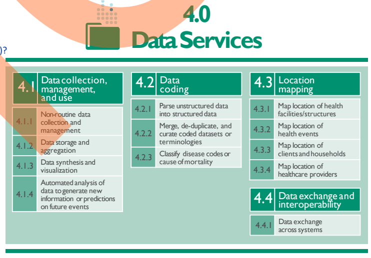


INTRODUCTION

What is Mobile Health (mHealth)?

World Health Organization (WHO). Classification of Digital Health Interventions V1.0. Geneva, Switzerland: WHO; 2018. Licence: CC BY-NC-SA 3.0 IGO. https://creativecommons.org/licenses/by-nc-sa/3.0/igo

INTRODUCTION

What is Mobile Health (mHealth)? Rapport Mobiele Gezondheidszorg en Telegeneeskunde : Mr HANTSON 2019

- **Telegeneeskunde:** verstrekking van de gezondheidszorg via het gebruik van informatie- en communicatietechnologie in de situatie waarbij de HCPs - patiënt zich fysiek niet op dezelfde plaats bevinden: zorg op afstand
  - tele-expertise: uitwisseling gezondheidsgegevens en medisch advise tussen HCP
  - Teleconsultatie: video communicatietussen HCP en patiënt
- **E-gezondheid of eHealth**: gebruik van informatie en communicatietechnologieën, met name internet, om de gezondheidszorg te ondersteunen en verbeteren
  - Focus niet op afstand, maar verbeteren in brede zin (EMD, e-voorschrift, practice management;…)
- **mHealth:** gebruik van mobiele componenten – gsm, smartphone, tablet, wearable, insidable = kenmerkend
  - Medische toepassingen: mobile medical applications
  - Gadgets

INTRODUCTION

What is Mobile Health (mHealth)? Rapport Mobiele Gezondheidszorg en Telegeneeskunde : Mr HANTSON 2019

- 8 Onderzoeksvragen:
  - Analyse van juridische situaties in verschillende Europese landen: Fr, NL, Ger, Por
  - Juridisch kader CE – markering, in België
  - Bescherming persoonsgegevens: GDPR – gebruik geanonimiseerde gegevens van mHealth?
  - Aansprakelijkheid van de actoren? Wijzingen nodig?
  - Criterium van fysieke aanwezigheid, wet 22 /08/2002 : te herzien? En hoe?
  - Moeten andere reglementaire aspecten aangepast worden?
    - Deontologische code zorgverleners,
    - Wet op ziekenhuizen (art 30?)
    - Mededingingsrecht?
  - Uitwerking validatiepiramide voor innovatieve mobiele toepassingen – aanpassingen regelgeving?
  - Hoe voormelde beperkingen inzake telegeneeskunde wegwerken? Terugbetaling?

INTRODUCTION

What is Mobile Health (mHealth)? 1/10/2023 RIZIV / INAMI Belgium

Onder **mobiele medische toepassing** verstaan we een software toepassing die:

• beschikt over een **CE-markering als medisch hulpmiddel** en is **genotificeerd bij het FAGG**

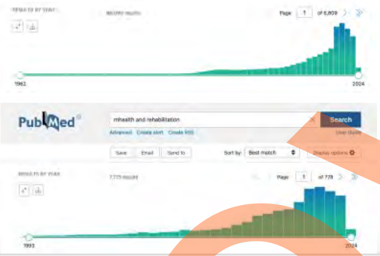
• een **patiënt toelaat om vanuit zijn eigen omgeving gezondheidsgerelateerde informatie** (al dan niet via sensoren) **te delen met een zorgverlener**

• een **zorgverlener toelaten** om bij een patiënt **vanop afstand een diagnose te stellen**, een **therapie toe te passen** of hem/haar **te monitoren via een medisch hulpmiddel** dat ontworpen is voor gebruik door de **patiënt in zijn eigen** omgeving

INTRODUCTION

What is Mobile Health (mHealth)?

Historical context and recent trends



MHEALTH REHABILITATION

BENEFITS

- Increased accessibility:
  - Delivers therapy directly to patients, overcoming transportation or mobility barriers
  - Enhanced engagement
  - Interactive exercises and real-time feedback promote patient motivation and adherence
- Personalized care: Tailored interventions based on individual needs and progress data
- Increased patient engagement
- Remote monitoring: Enables therapists to track patient progress and adjust plans remotely
- Cost-effectiveness: Reduces hospital stays and reliance on in-person therapy sessions

MHEALTH REHABILITATION

BENEFITS - FDA

- Reduce inefficiencies
- Reduce costs
- Improve access
- Increase quality
  - Enhanced data collection and analysis
  - Cost-effectiveness
- Make medicine more personalized for patients

MHEALTH REHABILITATION

FDA: Center for Devices and Radiological Health (CDRH)

- Software as a Medical Device (SaMD)
- Artificial Intelligence and Machine Learning (AI/ML) in Software as a Medical Device
- Cybersecurity
- Device Software Functions, including Mobile Medical Applications
- Health IT
- Medical Device Data Systems
- Medical Device Interoperability
- Telemedicine
- Wireless Medical Devices

MHEALTH REHABILITATION

Software functions (typically mobile apps) that transf
a regulated medical device → focus of the FDA's regul

• [https://www.fda.gov/medical-devices/device-software-functions-inc applications/examples-device-software-functions-fda-regulates](https://www.fda.gov/medical-devices/device-software-functions-including-mobile-medical-applications/examples-device-software-functions-fda-regulates)

EXPLORING MHEALTH APPLICATIONS

Subtypes

- Chronic disease management (e.g., diabetes, asthma, depression)
- Monitoring symptoms and medication adherence
- Remote consultations and interventions
- Educational resources and support communities
- Mental health and wellbeing
  - Anxiety and depression management apps
  - Mindfulness and meditation tools
  - Sleep tracking and improvement interventions

EXPLORING MHEALTH APPLICATIONS

Subtypes

- Public health initiatives
  - Vaccination campaigns and disease surveillance
  - Health promotion and behaviour change interventions
  - Contact tracing and outbreak management

MHEALTH REHABILITATION

APPLICATIONS

- Musculoskeletal:
  - Post-surgical rehab
  - Pain management
  - Low back pain
  - Balance training
- Neurological:
  - Stroke recovery
  - Aphasia therapy
  - Cognitive rehabilitation
  - Parkinson's disease management

MHEALTH REHABILITATION

APPLICATIONS

- Cardiac:
  - Cardiac rehabilitation
  - Heart failure management
  - Exercise monitoring
- Pulmonary:
  - COPD management
  - Respiratory exercises
  - Asthma control
- Mental health:
  - Anxiety and depression management, mindfulness training, sleep hygiene

MHEALTH REHABILITATION

TECHNOLOGY TOOLS

- Mobile apps:
  - Provide targeted exercises,
  - Educational resources
  - Progress tracking
  - Communication with therapists
- Wearable devices:
  - Track vital signs
  - Activity levels
  - Sleep patterns
  - Fall detection

MHEALTH REHABILITATION
TECHNOLOGY TOOLS

- Virtual reality (VR) and augmented reality (AR):
  - Immersive therapy experiences for motor skills training
  - Pain management
  - Phobia exposure
- Telehealth platforms:
  - Enable video consultations with therapists
  - Remote monitoring
  - Data sharing

MHEALTH REHABILITATION
CHALLENGES AND CONSIDERATIONS

- Technology access and literacy: Addressing disparities and providing support for older adults or those with low tech skills.
- Data privacy and security: Ensuring patient data is protected and used ethically.
- Reimbursement and regulatory issues: Establishing clear guidelines for mRehab integration into healthcare systems.
- Integration with traditional therapy: Ensuring mRehab complements, not replaces, in-person care.
- Evidence-based practices: Selecting interventions with proven effectiveness and tailoring them to individual needs.

MHEALTH REHABILITATION
BEST PRACTICE

- Collaboration: Interdisciplinary teams involving therapists, patients, and technology developers
- Patient-centered approach: Individualized interventions tailored to specific needs and preferences
- Evidence-based selection: Choosing mRehab tools with proven clinical efficacy
- Training and support: Providing proper training for therapists and patients on using mRehab tools
- Continuous evaluation and improvement: Regularly monitoring outcomes and updating protocols based on data

CHALLENGES AND CONSIDERATIONS

- Data privacy and security concerns
  - Protecting patient information and ensuring data confidentiality
  - Addressing potential vulnerabilities and breaches
- Digital divide and equity issues
  - Ensuring accessibility for different socioeconomic groups
  - Addressing technology literacy and skill barriers

CHALLENGES AND CONSIDERATIONS
Move_UP Covid case study presentation

VUB VRIJE UNIVERSITEIT BRUSSEL | UZ Universitair Ziekenhuis Brussel

TELEREHABILITATION IN BELGIUM
CURRENT STATE OF AFFAIRS

Marc Schiltz
UZ Brussel

TELEREHABILITATION IN BELGIUM

Future-proof?

Tesla hasn't technically promised fully self-driving cars in a single, definitive statement, but

•2013: Elon Musk publicly discusses the "Tesla Autopilot" system, mentioning its potential for future self-driving capabilities

•2014: Tesla unveils the first version of Autopilot, offering limited features like lane control and automatic parking

•2015: Musk predicts "complete autonomy" by 2018

•2016: Tesla expects to demonstrate full autonomy by the end of 2017

•2017: Musk predicts drivers will be able to sleep in their cars using Autopilot within two years

•2018 and later: Musk and Tesla continue making optimistic predictions

TELEREHABILITATION IN BELGIUM

Future-proof?

COVID-19: CONTINUITY OF PHYSIOTHERAPY

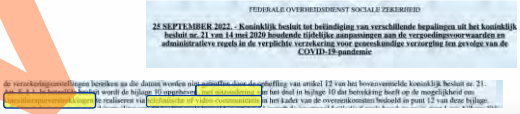
Hands-free: video or phone consultation

- Evaluation of patient through anamnesis
- Individualized exercise program & timing of ADL activities
- 2 contacts / week to stimulate patient adherence to the program
- Follow-up & adapt exercises
- Register useful parameters (ROM,…)

COVID-19: CONTINUITY OF PHYSIOTHERAPY

Hands-free: video or phone consultation

- 518011: ≥ 2 video contacts /week : weekly fee: 40€
- 518033: ≥ 2 phone contacts /week : weekly fee: 20€
- No supplements, No patient contribution, possible third-party payment



FEDERALE OVERHEIDSDIENST SOCIALE ZEKERHEID

25 SEPTEMBER 2022. - Koninklijk besluit tot beëindiging van verschillende bepalingen uit het koninklijk besluit nr. 21 van 14 mei 2020 houdende tijdelijke aanpassingen aan de vergoedingsvoorwaarden en administratieve regels in de verplichte verzekering voor geneeskundige verzorging ten gevolge van de COVID-19-pandemie

TELEREHABILITATION IN BELGIUM

VALIDATION PYRAMID

TELEREHABILITATION IN BELGIUM

December 2022: 36 registered Apps

Level 1: n = 23 Level 2: n = 12 Level 3: n = 1

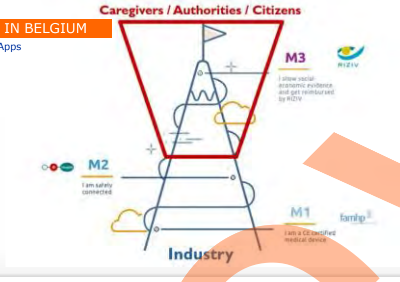
TELEREHABILITATION IN BELGIUM

February 2024: 35 registered Apps

Level 1 : n= 21 level 2: n= 14 Level 3: n = 0

TELEREHABILITATION IN BELGIUM

February 2024: 35 registered Apps



"MOBILE APP FOR REHAB RCT"

Stuurgroep revalidatie via mobiele applicatie na arthroplastie
Groupe de pilotage revalidation via application mobile après arthroplastie

CONVENTION & FUNDER
- Temporary coverage of mobile app for rehabilitation with evidence development (Study, Phase I)
- Definitive reimbursement of mobile app?

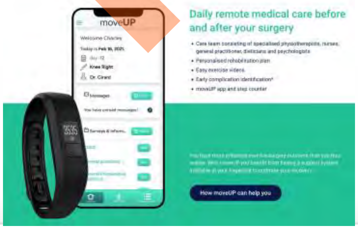
TRIAL SPONSOR
- Effectiveness of mobile applications on rehabilitation outcomes (PROMS)
- In collaboration with Cel Biostatistiek, Ugent

HEALTH TECHNOLOGY ASSESSMENT (HTA)
- More extensive effectiveness and cost-effectiveness analysis
- Significant savings for the healthcare payer?

MOBILE APP
- Personalized rehabilitation after hip & knee replacement at home through daily follow-up
- CE-marked

MOVEUP.CARE

Trial Inclusion criteria

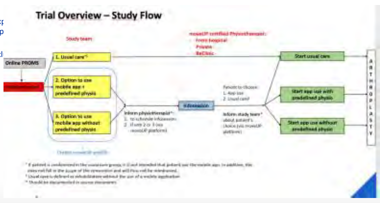


- **Knee/hip arthroplasty** planned between the next 1 to 8 weeks (UKA, BKA, TKA, THA)
- Does not exclude upfront the possibility whereby **part of the rehabilitation is performed without a physical therapist physically being present**.
- Able to complete the patient reported outcomes online (**computer literacy test**)
- Easy and daily **access to the internet**

TRIAL OVERVIEW

Exclusion Criteria & Problems

- Conditions or procedures that are exp operative procedure, postoperative p condition, surgery)
- Impossible to use K conjointly → excl convention
- Patient enrolled in
  - "Maison médicale"
  - "Wijkgezondheidscentrum"
- Complicated study flow



TRIAL OVERVIEW

Exclusion Criteria & Problems

Sites open for recruitment

12 sites open

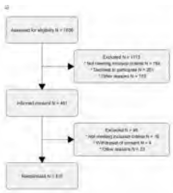
- AZ Alma Eeklo
- AZ Damiaan Oostende
- AZ Maria Middelares
- AZ Monica Deurne
- AZ Sint-Jan Brugge
- CHIREC Braine-L'Alleud
- CHIREC Delta
- Jan Yperman ZH
- UZ Gent
- CHU Liège
- Grand Hôpital de Charleroi
- UCL Saint-Luc

TRIAL OVERVIEW

Exclusion Criteria & Problems

TRIAL OVERVIEW

Exclusion Criteria & Problems



1636 patients assessed for eligibility

1220 patients excluded (74.6%)
- 772 were not meeting the inclusion criteria (47.2%)
- 255 declined to participate (15.6%)
- 193 excluded for other reasons (11.8%)

864 patients meeting the inclusion criteria
- 255 declined to participate (29.5%)

416 patients randomized (25.4%)

TRIAL OVERVIEW

Exclusion Criteria & Problems: n = 1175 , of 1636 assessed patients

Reasons for excluding patients from informed consent (screening log data)

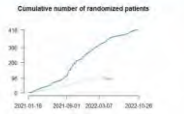
Reason for exclusion from informed consent	[n/N (%)]
Patient wants to rehabilitate with own physiotherapist / believes he/she is not able to do the excercises alone	384/1175 (33%)
No specific reason / reason not specified	179/1175 (15%)
Stay in rehab centre	119/1175 (10%)
Patient indicates that he/she is not computer literate: has no internet, has no smartphone/tablet, not able to work with smartphone, digital phobic, he/she is afraid he/she won't be able to work with the app	116/1175 (9.9%)
Study team has not enough time to include patient, surgery planned earlier	65/1175 (5.5%)
PI believes patient is too old / is unsuitable	61/1175 (5.2%)
Concomitant medical condition	54/1175 (4.6%)
Other: patient believes it is better for him not to participate, difficult in combination with taking care of husband (cancer), not interested in participating in study, too complicated, working in shifts …	41/1175 (3.5%)
Other planned surgery within 6 months	31/1175 (2.6%)
Not able to reach patient	30/1175 (2.6%)
Surgery cancelled or postponed	20/1175 (1.7%)
Already participated in the study / participation in competitive study	14/1175 (1.2%)
No interest in rehabilitation with app	12/1175 (1%)
Patient does not want to come for intake session or lives too far	12/1175 (1%)
Revision surgery	12/1175 (1%)
Patient has no sufficient knowledge of Dutch, French, German or English	10/1175 (0.85%)
Patient wants to use moveUP outside the study	7/1175 (0.6%)
Patient has no Belgian NN number	7/1175 (0.6%)
Perioperative surgery	1/1175 (0.085%)

ANALYSIS OF TRIAL DATA

Deadlines:

- mid 2023: latest data for eCRF
- 2024: IMA-AIM coupling

Cumulative number of randomized patients by calendar date



Power with the current sample size

Comparison	Endpoint	Calculated total per protocol sample size	Calculated total ITT sample size	Current total ITT sample size	Forecasts per protocol sample size	Power
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	221	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	221	[illegible]	[illegible]

[illegible]

BEYOND THE TRIAL 1/10/2022 – 30/06/2023

- ≥ 1 physical physiotherapy session /week for 4weeks, than 1 every 2 weeks
- Bundled payment includes:
  - Follow-up, includes Mobile App & Wearable
  - Telerehabiliation
  - All PT sessions
  - Final report
- Prescription by orthopedic surgeon or PMR

a) Revalidation avec le soutien de l'application mobile et un nombre défini de séances classiques régulières de kinésithérapie avec présence physique

Pseudo-code	Libellé	Tarif	Part personnelle RP	Part personnelle RNP
567475	Traitement et suivi du patient via l'application mobile suivant l'hospitalisation pour une arthroplastie primaire du genou endéans les 4 premières semaines après l'hospitalisation, par période de 2 Semaines	100 EUR	6,40 EUR	17,60 EUR
567490	Traitement et suivi du patient via l'application mobile suivant l'hospitalisation pour une arthroplastie primaire du genou à partir de la 5ième semaine après l'hospitalisation, par période de 2 semaines	75 EUR	5,60 EUR	15,40 EUR
567512	Traitement et suivi du patient via l'application mobile suivant l'hospitalisation pour une arthroplastie primaire du genou à partir de la 5ième semaine après l'hospitalisation, par période de 2 semaines	57,50 EUR	5,60 EUR	15,40 EUR

BEYOND THE TRIAL 1/10/2022 – 30/06/2023

INTRODUCTION

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• een **zorgverlener toelaten** om bij een patiënt **vanop afstand een diagnose te stellen**, een **therapie toe te passen** of hem/haar **te monitoren via een medisch hulpmiddel** dat ontworpen is voor gebruik door de **patiënt in zijn eigen** omgeving

> 1/10/2023

Wie kan een aanvraag indienen?

- **Fabrikanten** en **verdelers** van mobiele, medische toepassingen die geresisteerd zijn bij het FAGG
- **Wetenschappelijke verenigingen**
- **Beroepsorganisaties**:
  - vereniging van zorgverleners met als rechtsvorm beroepsvereniging of vzw erkend als beroepsvereniging of als federatie van beroepsverenigingen
  - zetelt als representatieve beroepsorganisatie in één van de organen van het RIZIV
- Leden van de multidisciplinaire werkgroep verantwoordelijke voor de behandeling van de aanvragen.
- **Ziekenhuis**

> 1/10/2023

Hoe kan u een aanvraag voor een mobiele, medische toepassing indienen?

- Juiste formulier in te vullen (tijdelijke of definitieve terugbetaling)
- **De tijdelijke terugbetaling** is bedoeld voor toepassingen met een **innovatief karakter**, waarvoor al evidentie aanwezig is, maar er nog enkele onzekerheden zijn.
- Wanneer fabrikanten en verdelers of ziekenhuizen een dergelijke aanvraag indienen:
  - Steun zijn vanuit een wetenschappelijke – of beroepsvereniging
  - Standaardduur van terugbetaling van drie jaar, waarvan gemotiveerd kan worden afgeweken
  - Elke 18 maanden een tussentijdse evaluatie
- Ten laatste zes maanden voor het einde van de tijdelijke terugbetaling een aanvraag voor definitieve terugbetaling en een evaluatierapport in
- https://www.riziv.fgov.be/nl/professionals/andere-professionals/fabrikanten-en-verdelers-van-medische-hulpmiddelen/mobiele-medische-toepassingen-uw-aanvraag-indienen#wat-is-een-mobiele-medische-toepassing

CHALLENGES AND CONSIDERATIONS

mHealth Follow-up after Covid-19 discharge: case study

- Overreliance on technology and potential downsides
  - Importance of human interaction and clinical judgment
  - Avoiding overtreatment and information overload

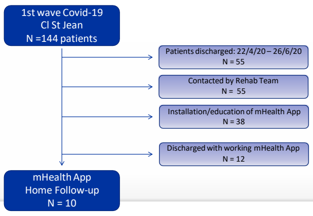
MHEALTH APP FOR FOLLOW-UP OF COVID-19 PATIENTS RETURNING HOME AFTER HOSPITAL DISCHARGE: AN IMPLEMENTATION STUDY – CASE SERIES

Dr Marc Schiltz
Clinique St Jean - Brussels
UZ - Brussels

FLOWCHART MOBILE HEALTH FOLLOW-UP

- Patient anxiety is substantially increased during a pandemic.
- In times of uncertainty, Structure provides relief

NEJM Catalyst, mai 2020



PATIENTS DEMOGRAPHICS: HOME FOLLOW-UP

N = 12

Average age: 66,5 y (SD 17,08)

Native French or Dutch speakers: 3/12

Follow-up at home:

- N = 10
- 17,3 days (SD 8,8d)
- Discharge <–> last questionnaire completed

BARRIERS TO IMPLEMENTATION

Language barriers

Digital issues:

- No working smartphone
- No email account
- No website proposition
- Limited time to educate patients, in absence of help from family/friends
- No audio-messages, only written chat function

PHYSICIANS: QUESTIONNAIRES + NPS (NET PROMOTER SCORE)

NPS : all patients : -1

NPS : "digitally-savvy" patient : 67

NPS : user-friendliness MoveUp: 67

Standardized questionnaires:

- ✓ Easy to use
- ✓ Patient feedback very positive
- ✓ Patients need intrinsic motivation to fill out questionnaires

PATIENTS: QUESTIONNAIRES + NPS (NET PROMOTER SCORE)

NPS : how easy to install: -67

NPS : would you recommand this solution to a friend: -33

General remarks for NPS:

- Low number of responses:
  - Digital gap
  - Lack of coherence in answers from doctors during chat

Standardized questionnaires:

- ✓ Secure feeling, trust relationship
- ✓ For digital savvy patients, easy to use & experienced as a great tool

TAKE HOME MESSAGES

Make sure you know your patient group

Education takes time, also for digital matters

Without digital issues:

- Very satisfied patients, physicians
- Integration into daily workflow
- Importance of coherent message

REFERENCES

& ACKNOWLEDGMENTS

A Paradigm for the Pandemic: A Covid-19 Recovery Unit. NEJM Catalyst. 2020; DOI: 10.1056/CAT.20.0238

Application of telemedicine during the coronavirus disease epidemics: a rapid review and meta-analysis. Ann of Transl Med. 2020; http://dx.doi.org/10.21037/atm-20-3315

Delivering Telerehabilitation to COVID-19 Inpatients: A Retrospective Chart Review Suggests It Is a Viable Option. HSSJ; DOI 10.1007/s11420-020-09774-4

Special thank you to :

- Dr C Sanida, chief medical information officer - Cl St Jean
- S Creve, chief technology officer – Cl St Jean
- CE Winandy & R De Saer from moveUP

No conflict of interests

ETHICAL CONSIDERATIONS AND BEST PRACTICES

REHABILITATION

* Key ethical principles for mHealth development and use
  * Transparency, informed consent, and data ownership
  * Non-discrimination and fair access
  * Respect for patient autonomy and privacy
* Best practices for implementing mHealth effectively
  * Integration with existing healthcare systems
  * User-centered design and usability
  * Evidence-based approach and rigorous evaluation

ADDITIONAL RESOURCES

REHABILITATION

- https://www.who.int/teams/digital-health-and-innovation/smart-guidelines
- https://www.kngf.nl/kennisplatform/richtlijnen/zorg-op-afstand/diagnostisch-proces/toepassen-van-zorg-op-afstand
- WHO Consolidated telemedicine implementation guide: https://www.who.int/publications/i/item/9789240059184
- KCE REPORT 362As HEALTH TECHNOLOGY ASSESSMENT: 2023 https://kce.fgov.be/en/evaluation-of-digital-medical-technologies

DANK U

VRIJE UNIVERSITEIT BRUSSEL

Universitair Ziekenhuis Brussel

Part 6 Artificial Intelligence

1 Introduction to this part

How:

- online synchronous (live) (see online schedule)
- followed by online (live) working sessions (see online schedule)
- After every lecture and for every working session a ppt will be included

2 Lecture 1: introduction

2.1 What is AI?

2.1.1 Definitions

2.1.2 Timeline

2.2 Supervised learning

2.3 Learning a decision boundary from labeled data

2.4 How to find the optimal decision boundary

2.5 Datapoints

2.6 Clustering

2.7 Additional information, slides, articles

ARTIFICIAL INTELLIGENCE

VRIJE UNIVERSITEIT BRUSSEL

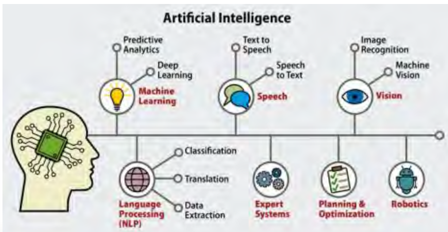
LECTURE 1: INTRO

2

WHAT IS AI?

3

6

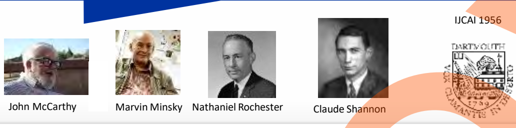


SOME DEFINITIONS

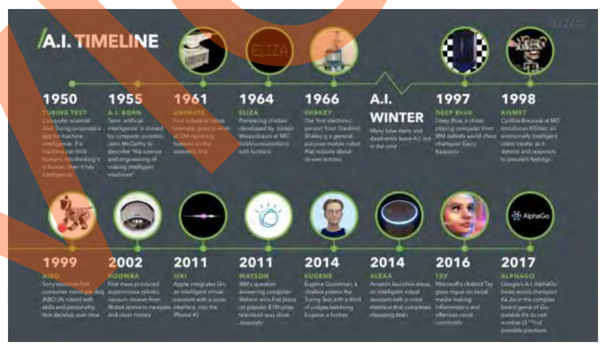
- Intelligence: 'The capacity to learn and solve problems.'
- Artificial Intelligence: "The simulation of human intelligence by machines, the study and design of intelligent agents."
  - The ability to solve problems
  - The ability to act rationally
  - The ability to act like humans
  - …
- Machine Learning: "The study and design of intelligent agents that make decisions based on data."

" We propose that a 2 month, 10 man study of artificial intelligence be carried out during the summer of 1956 at Dartmouth College in Hanover, New Hampshire. The study is to proceed on the basis of the conjecture that every aspect of learning or any other feature of intelligence can in principle be so precisely described that a machine can be made to simulate it. An attempt will be made to find how to make machines use language, form abstractions and concepts, solve kinds of problems now reserved for humans, and improve themselves. We think that a significant advance can be made in one or more of these problems if a carefully selected group of scientists work on it together for a summer."

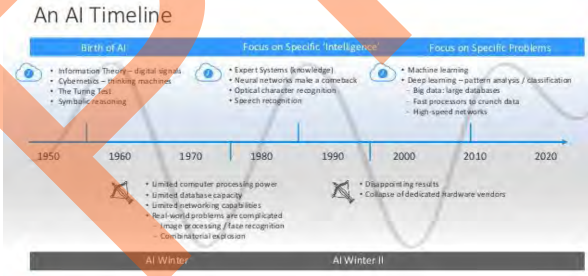
IJCAI 1956



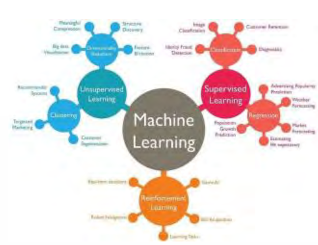
John McCarthy Marvin Minsky Nathaniel Rochester Claude Shannon



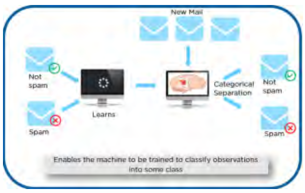
An AI Timeline



harmon.ie

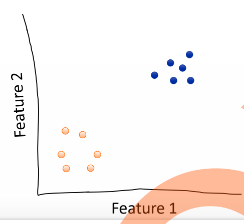


SUPERVISED LEARNING



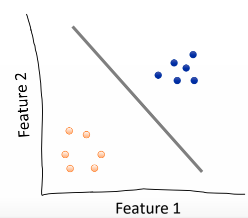
LEARNING A DECISION BOUNDARY FROM LABELED DATA

Index	Feature 1	Feature 2	class
0	50.3	8.5	+
1	12.1	86.4	+
2	8.6	76.6	-
3	69.8	6.5	-
4	99.1	10.2	+
5	10.1	87.6	-
6	8.4	64.5	+
7	6.5	75.4	+
8	83.5	8.4	-
9	92.1	2.1	+
10	6.6	75.5	-
11	6.7	92.4	+



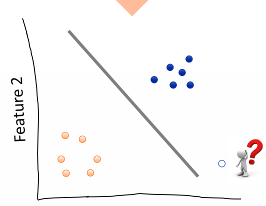
LEARNING A DECISION BOUNDARY FROM LABELED DATA

Index	Feature 1	Feature 2	class
0	50.3	8.5	+
1	12.1	86.4	+
2	8.6	76.6	-
3	69.8	6.5	-
4	99.1	10.2	+
5	10.1	87.6	-
6	8.4	64.5	+
7	6.5	75.4	+
8	83.5	8.4	-
9	92.1	2.1	+
10	6.6	75.5	-
11	6.7	92.4	+



LEARNING A DECISION BOUNDARY FROM LABELED DATA

Index	Feature 1	Feature 2	class
0	50.3	8.5	+
1	12.1	86.4	+
2	8.6	76.6	-
3	69.8	6.5	-
4	99.1	10.2	+
5	10.1	87.6	-
6	8.4	64.5	+
7	6.5	75.4	+
8	83.5	8.4	-
9	92.1	2.1	+
10	6.6	75.5	-
11	6.7	92.4	+

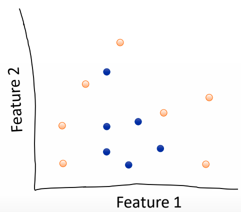


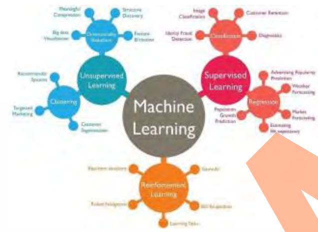
HOW TO FIND THE OPTIMAL DECISION BOUNDARY

DIFFERENT APPROACHES

- Depends on how you define "optimal"
  - Minimize the nr of misclassifications in the training set
  - Maximize the margin, i.e. the distance between the boundary and the samples of each class
  - ...
- A very large amount of methods exist for solving this problem
  - Decision trees
  - Neural networks
  - Support vector machines

IN REAL PROBLEMS





"DATAPOINTS ARE A BIT LIKE COCONUTS"

Another data point

One data point

EACH DATAPOINT HAS FEATURES

1. Color
2. Size
3. Amount of hair
4. Cut on top

DATASETS ARE LIKE PILES OF COCONUTS

BUT THEY ACTUALLY ARE MATRICES

Index	Color	Size	Hair	Cut on Top
0	Green	52.6	False	True
1	Brown	18.5	True	False
2	Grey	45.4	True	False
3	Green	13.6	False	True
4	Green	22.6	False	False
5	Brown	16.5	True	False
6	Grey	16.4	True	False

DATA POINTS ARE UNLABELED IF WE DON'T KNOW THEIR "TYPE"

1. Color
2. Size
3. Amount of hair
4. Cut on top

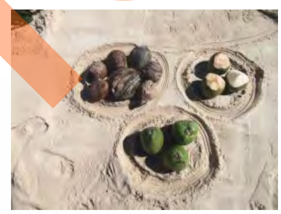
DATA POINTS ARE UNLABELED IF WE DON'T KNOW THEIR "TYPE"

1. Color
2. Size
3. Amount of hair
4. Cut on top

This is a rotten coconut. But that piece of information is missing from our dataset

Clustering: Grouping together similar data-points

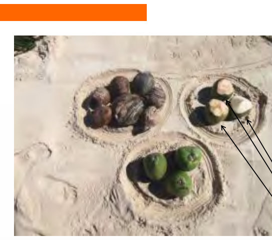
CLUSTERING



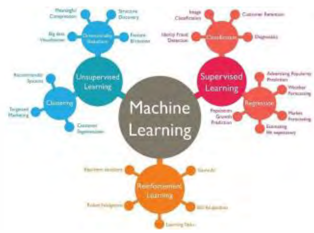
CLUSTERING

Features are similar

CLUSTERING

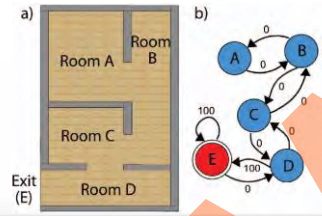


Features are similar



REINFORCEMENT LEARNING

LEARNING FROM EXPERIENCE: STATE – ACTION – REWARD - POLICY



3 Lecture 2: Search and chess

3.1 Introduction

3.2 Method

3.3 Problem

3.4 Solution

3.5 Limitations

3.6 Additional information, slides, articles

ARTIFICIAL INTELLIGENCE

VRIJE UNIVERSITEIT BRUSSEL

SEARCH AND CHESS

An example of Artificial Intelligence, without machine learning …

This is about how a computer can play chess, not about how it can learn how to play chess.

HOW CAN A COMPUTER PLAY BOARD GAMES LIKE CHESS?

- Game is considered to be intelligent. It doesn't really learn.
- But 'intelligent' behavior is a good start.
- It has actually become easy to make your own chess game that beats you.

THE MECHANICAL TURK
WOLFGANG VON KEMPELEN, 1770

THE MECHANICAL TURK
WOLFGANG VON KEMPELEN, 1770

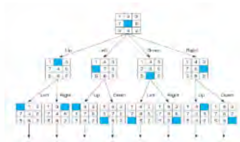
1951: "GAME AI"

- First computer chess program (Dietrich Prinz)
- First computer checkers program (Christopher Stratchey)
- Start of the use of computer games as a benchmark for AI


ARTICLE

Mastering the game of Go with deep neural networks and tree search

LET US START LESS AMBITIOUS ...



METHODS TO SEARCH THE TREE

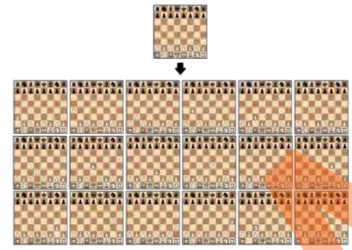
- Depth first search
- Breadth first search
- Heuristic search

SOME OBSERVATIONS

- If there is a goal state, breadth first search will find the path to the goal which has the least number of steps -> shortest path.
- This is not the same as evaluating the least number of nodes.
- Heuristic search: quality of the solution depends on the quality of the heuristic

WHAT DOES IT MEAN FOR GAMES?

- Typically, board games like chess can easily be modelled as state space search problems.
  - The state is the board
  - The actions are moving each of the pieces in any valid direction
  - The goal state is the winning state.
- Good heuristics exist for chess etc, based on the nr and kind of pieces, …
- Turn after turn, you make the first move on the path towards the goal.



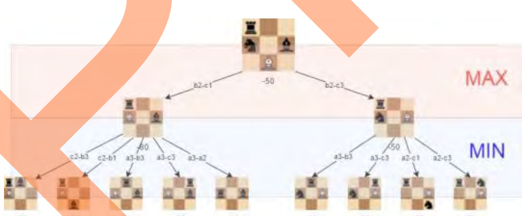
https://www.freecodecamp.org/news/simple-chess-ai-step-by-step-1d55a9266977/

PROBLEM

- "Turn after turn, you make the first move on the path towards the goal"
  - We forget about the fact that there is an opponent in games.
  - You don't know what the opponent will do, you can't predict
  - If the opponent is smart, you should assume that he also wants to win.
  - Tree search does not work

THE SOLUTION: MINIMAX TREES

- A method that takes into account the opponent's behavior in the three search.
- Opponent's behavior cannot be known, but it is modelled:
  - We assume that the computer player is rational: he maximizes the quality of the state.
  - We assume that the opponent is rational: he maximizes the quality of the state from his perspective.
  - That means he minimizes the quality of the state (for the computer's perspective).



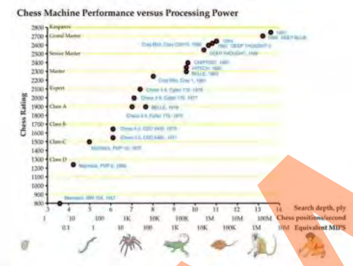
https://www.freecodecamp.org/news/simple-chess-ai-step-by-step-1d55a9266977/

LIMITATIONS

- Computer chess heavily depends on the minimax algorithm.
- The search spaces (the possible boards to evaluate) however becomes huge!
- Every turn, a player can make on average about 35 valid moves in chess.
- Branching factor of 35, means that looking 4 moves ahead gives 35^4 = 1.5M moves to check. Looking 8 moves ahead, means 10^12.
- The quality of the gameplay depends on the computational power.
- Minimax alone is not enough. The next trick to use is alpha-beta pruning.

DEEP BLUE IN BRIEF

- Evaluates the quality of 200M positions per second in terms of
  - Material
  - Position
  - King Safety
  - Tempo



4 Lecture 3: Regression

4.1 Example

4.2 Looking at the same data differently

4.3 Building a hypothesis

4.4 Solving a regression problem

4.5 What if there are multiple variables?

4.6 Overfitting

4.7 Additional information, slides, articles

MIAMI-II AI

VRIJE UNIVERSITEIT BRUSSEL

REGRESSION

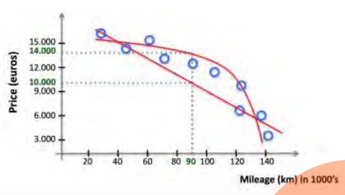
Supervised learning

Not predicting a class but a continuous value

(based on slides by N. Deligianis)

EXAMPLE PROBLEM

PREDICTING THE PRICE OF A SECOND-HAND CAR



LOOKING AT THE SAME DATA DIFFERENTLY

WHAT IS THE BEST PREDICTED Y FOR A GIVEN X?

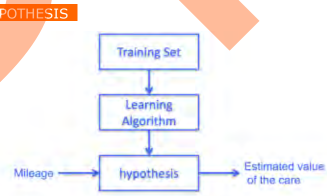
input variable or feature or regressor (x) — response or predicted variable (y)

Mileage (km) in 1000's	Price (euros)
25	16.000
105	11.500
120	6.000
140	3.000
45	13.500

n training samples

$(x^{(i)}, y^{(i)})$ – the i-th training example.

BUILDING A HYPOTHESIS



Q1: Is the mileage a good feature?

Q2: What is a good function for the hypothesis?

BUILDING A HYPOTHESIS

To model **linear** relationships between variables, we consider a simple parametric regression model:

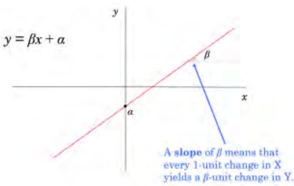
Hypothesis – linear function

$$Y = f(X;\theta) + \varepsilon$$

- Y: *Response* or *predicted* variable
- X: *Regressor* or *input* variable
- θ: Model *parameters*
- ε: *Error* or *residual* model

A LINEAR RELATIONSHIP

$y = \beta x + \alpha$



SOLVING A REGRESSION PROBLEM

We have n observed values x_i corresponding to the n estimates of y_i

$$\hat{y}_i = \alpha + \beta x_i$$

The corresponding residual errors are

$$\varepsilon_i = y_i - \hat{y}_i$$

Optimal estimates: Minimization of the sum of the squared residuals (SSR)

$$\text{SSR} = \textstyle\sum_{i=1}^{n} (y_i - \hat{y}_i)^2$$

The optimal estimates of the parameters are

$$\hat{\beta} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sum_{i=1}^{n}(x_i - \bar{x})^2} \qquad \hat{\alpha} = \bar{y} - \hat{\beta}\bar{x}$$

DERIVATION ...

$$[\, \hat{\alpha} \;\; \hat{\beta} \,] = \underset{\alpha,\beta}{\text{argmin}} \; \textstyle\sum_{i=1}^{n} (y_i - \hat{y}_i)^2$$

$$\begin{aligned} SSR &= \sum_{i=1}^{n} (y_i - (\alpha + \beta x_i))^2 \\ &= \sum_{i=1}^{n} \left(y_i^2 - 2y_i(\alpha + \beta x_i) + \alpha^2 + 2\alpha\beta x_i + \beta^2 x_i^2\right) \end{aligned}$$

$$\begin{aligned} \frac{\partial SSR}{\partial \alpha} &= \sum_{i=1}^{n} (-2y_i + 2\alpha + 2\beta x_i) \\ 0 &= \sum_{i=1}^{n} \left(-y_i + \hat{\alpha} + \hat{\beta} x_i\right) \\ 0 &= -n\bar{y} + n\hat{\alpha} + \hat{\beta} n \bar{x} \\ \hat{\alpha} &= \bar{y} - \hat{\beta}\bar{x} \end{aligned}$$

DERIVATION ...

$$\begin{aligned} \frac{\partial SSR}{\partial \beta} &= \sum_{i=1}^{n} \left(-2x_i y_i + 2\,\alpha x_i + 2\,\beta\, x_i^2\right) \\ 0 &= -\sum_{i=1}^{n} x_i y_i + \hat{\alpha} \sum_{i=1}^{n} x_i + \hat{\beta} \sum_{i=1}^{n} x_i^2 \\ 0 &= -\sum_{i=1}^{n} x_i y_i + (\bar{y} - \hat{\beta}\,\bar{x}) \sum_{i=1}^{n} x_i + \hat{\beta} \sum_{i=1}^{n} x_i^2 \\ \hat{\beta} &= \frac{\sum_{i=1}^{n} x_i (y_i - \bar{y})}{\sum_{i=1}^{n} x_i (x_i - \bar{x})} \end{aligned}$$

WHAT IF THERE ARE MULTIPLE VARIABLES?

feature (x_1) · feature (x_2) · feature (x_3) · response or predicted variable (y)

Num. cylinders	Num. of doors	Mileage (km) in 1000's	Price (euros)
6	3	25	16.000
12	5	105	11.500
8	5	120	6.000
8	3	140	3.000
12	3	45	13.500

n training samples

$(x_1^{(i)}, x_2^{(i)}, x_3^{(i)}, \ldots, x_p^{(i)}, y^{(i)})$ – the i-th training example.

p input variables, a.k.a. features

WHAT IF THERE ARE MULTIPLE VARIABLES?

Num. cylinders	Num. of doors	Mileage (km) in 1000's	Price (euros)
6	3	25	16.000
12	5	105	11.500
8	5	120	6.000
8	3	140	3.000
12	3	45	13.500

n training samples

$$y_i = \beta_0 + \beta_1 x_{i,1} + \beta_2 x_{i,2} + \ldots + \beta_{p-1} x_{i,p-1} + \varepsilon_i$$

$\beta = (\beta_0, \beta_1, \ldots, \beta_p)^T$

Error term

WHAT IF THERE ARE MULTIPLE VARIABLES?

Num. cylinders	Num. of doors	Mileage (km) in 1000's	Price (euros)
6	3	25	16.000
12	5	105	11.500
8	5	120	6.000
8	3	140	3.000
12	3	45	13.500

n training samples

$$\begin{bmatrix} 16.000 \\ 11.500 \\ 6.000 \\ 3.000 \\ 13.500 \end{bmatrix} = \begin{bmatrix} 1 & 25 & 3 & 6 \\ 1 & 105 & 5 & 12 \\ 1 & 120 & 5 & 8 \\ 1 & 140 & 3 & 8 \\ 1 & 45 & 3 & 12 \end{bmatrix} \times \begin{bmatrix} \beta_0 \\ \beta_1 \\ \beta_2 \\ \beta_3 \end{bmatrix} + \begin{bmatrix} \varepsilon_0 \\ \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \end{bmatrix}$$

$$y_i = \beta_0 + \beta_1 x_{i,1} + \beta_2 x_{i,2} + \ldots + \beta_{p-1} x_{i,p-1} + \epsilon_i.$$

WHAT IF THERE ARE MULTIPLE VARIABLES?

Parameter estimation is done by minimizing the sum of squared residuals (RSS).

$$\text{SSR}(\beta) = \sum_{i=1}^{N} \left(y_i - \beta_0 - \sum_{j=1}^{p} x_{ij}\beta_j\right)^2$$

$$\text{SSR}(\beta) = (\mathbf{y} - \mathbf{X}\beta)^T(\mathbf{y} - \mathbf{X}\beta)$$

Response vector: N-vector of outputs in the training set.

Data matrix:

$$\mathbf{X} = \begin{pmatrix} 1 & X_{11} & X_{12} & \cdots X_{1p} \\ 1 & X_{21} & X_{22} & \cdots X_{2p} \\ & & \vdots & \\ 1 & X_{n1} & X_{n2} & \cdots X_{np} \end{pmatrix}$$

WHAT IF THERE ARE MULTIPLE VARIABLES?

We find the (unique) optimal parameters

$$\hat{\beta} = (\mathbf{X}^T\mathbf{X})^{-1}\mathbf{X}^T\mathbf{y}.$$

The matrix $\mathbf{X}(\mathbf{X}^T\mathbf{X})^{-1}\mathbf{X}^T$ is called ***pseudo-inverse*** or ***Moore-Penrose*** matrix.

WHAT IF THERE ARE MULTIPLE VARIABLES?

The Problem of Overfitting

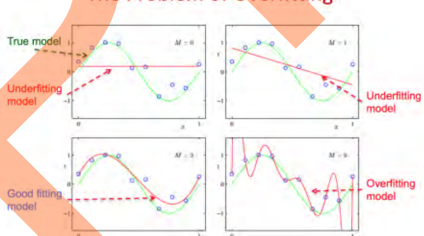
Thus, one could say that ***having more predictors would lead to better estimates!***

NO!!!

Assuming too many coefficients – or degrees of freedom – with respect to the number of observations you will end up with

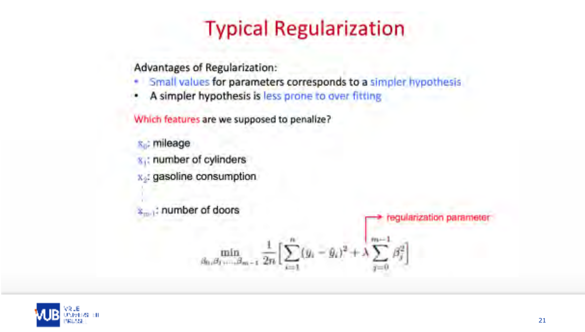
- Too many predictor variables
- Complicated relations (interactions, nonlinear effects) between response variable and predictors that do not exist in the population!

The Problem of Overfitting



Dealing with Overfitting

- Reduce number of features
  - Manually select which features to keep (model selection algorithms)
  - But, in reducing the number of features we lose some information (Ideally select those features which minimize data loss, but even so, some info is lost)
- Regularization
  - Keep all features, but reduce magnitude of parameters
  - Works well when we have a lot of features, each of which contributes a bit to prediction


Typical Regularization
Advantages of Regularization:
Small values for parameters corresponds to a simpler hypothesis
A simpler hypothesis is less prone to over fitting
Which features are we supposed to penalize?
x_0: mileage
x_1: number of cylinders
x_2: gasoline consumption
x_{m-1}: number of doors
regularization parameter
$$\min_{\beta_0, \beta_1, \ldots, \beta_{m-1}} \frac{1}{2n} \left[\sum_{i=1}^{n} (y_i - \hat{y}_i)^2 + \lambda \sum_{j=0}^{m-1} \beta_j^2 \right]$$
21

5 Lecture 4: Supervised learning

5.1 Support vector machines (svm)

5.2 The linear support vector machine (LSVM)

5.3 Soft Margin Classification

5.4 Hard margin vs soft margin

5.5 Additional information, slides, articles

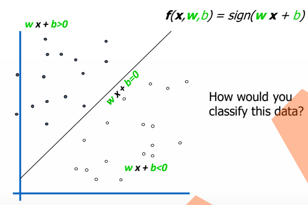
SUPERVISED LEARNING

Support vector machines as an example for classification

BACK TO SUPERVISED LEARNING

SUPPORT VECTOR MACHINES

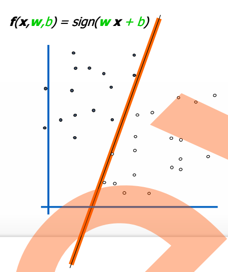
- denotes +1
- ◦ denotes -1



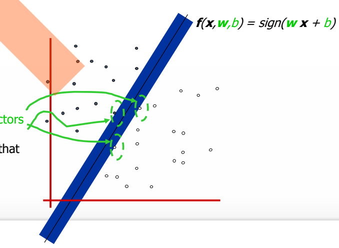
How would you classify this data?

THE MARGIN

Define the margin of a linear classifier as the width that the boundary could be increased by before hitting a datapoint.

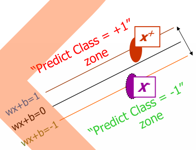


THE LINEAR SUPPORT VECTOR MACHINE (LSVM)



Support Vectors are those datapoints that the margin pushes up against

LINEAR SVM MATHEMATICALLY



M=Margin Width

What we know:

w *.* ***x***$^+$ *+ b = +1*

w *.* ***x***$^-$ *+ b = -1*

w *. (**x**$^+$-**x**$^-$) = 2*

$$M = \frac{(x^+ - x^-)\cdot w}{|w|} = \frac{2}{|w|}$$

LINEAR SVM MATHEMATICALLY

WHAT DO WE NEED?

1. Correctly classify all training data
2. Maximize the margin

LINEAR SVM MATHEMATICALLY

WHAT DO WE NEED?

1. Correctly classify all training data

$$wx_i + b \geq 1 \quad \text{if } y_i = +1$$
$$wx_i + b \leq 1 \quad \text{if } y_i = -1$$

$$\Rightarrow \; y_i(wx_i + b) \geq 1$$

2. Maximize the margin M

$$M = \frac{2}{|w|}$$

equivalent to minimize $\frac{1}{2}w^t w$

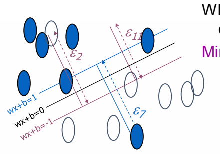
LSVM AS AN OPTIMIZATION PROBLEM

Minimize $\Phi(w) = \frac{1}{2}w^t w$

Subject to $y_i(wx_i + b) \geq 1 \quad \forall i$

SOFT MARGIN CLASSIFICATION

***Slack variables** ξi* **can be added to allow misclassification of difficult or noisy examples.**



What should our quadratic optimization criterion be?

Minimize

$$\frac{1}{2}\mathbf{w}.\mathbf{w} + C\sum_{k=1}^{R}\varepsilon_k$$

Hard Margin v.s. Soft Margin

- **The old formulation:**

  Find **w** and *b* such that
  $\mathbf{\Phi(w)} = \frac{1}{2}\, \mathbf{w}^T\mathbf{w}$ is minimized and for all $\{(\mathbf{x_i}, y_i)\}$
  $y_i(\mathbf{w}^T\mathbf{x_i} + b) \geq 1$

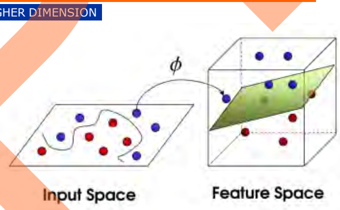
- **The new formulation incorporating slack variables:**

  Find **w** and *b* such that
  $\mathbf{\Phi(w)} = \frac{1}{2}\, \mathbf{w}^T\mathbf{w} + C\Sigma\xi_i$ is minimized and for all $\{(\mathbf{x_i}, y_i)\}$
  $y_i(\mathbf{w}^T\mathbf{x_i} + b) \geq 1 - \xi_i$ and $\xi_i \geq 0$ for all i

- **Parameter *C* can be viewed as a way to control overfitting.**

BUT MOST PROBLEMS ARE NOT LINEARLY SEPERABLE

MAP TO HIGHER DIMENSION



6 Lecture 5: Decision trees and random forests

6.1 Introduction

6.2 Decision trees

6.3 Overfitting

6.4 Bagging, boosting and Random Forests

6.5 Additional information, slides, articles

MIAMI 2 AI

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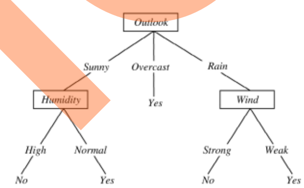
DECISION TREES AND RANDOM FORESTS

Based on Machine Learning 10601
Recitation 8
Oct 21, 2009

lecture slides for textbook *Machine Learning*, ©Tom M. Mitchell, McGraw Hill, 1997

Day	Outlook	Temperature	Humidity	Wind	PlayTenn
D1	Sunny	Hot	High	Weak	No
D2	Sunny	Hot	High	Strong	No
D3	Overcast	Hot	High	Weak	Yes
D4	Rain	Mild	High	Weak	Yes
D5	Rain	Cool	Normal	Weak	Yes
D6	Rain	Cool	Normal	Strong	No
D7	Overcast	Cool	Normal	Strong	Yes
D8	Sunny	Mild	High	Weak	No
D9	Sunny	Cool	Normal	Weak	Yes
D10	Rain	Mild	Normal	Weak	Yes
D11	Sunny	Mild	Normal	Strong	Yes
D12	Overcast	Mild	High	Strong	Yes
D13	Overcast	Hot	Normal	Weak	Yes
D14	Rain	Mild	High	Strong	No

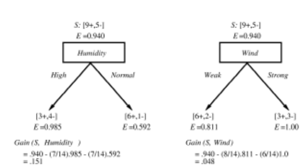


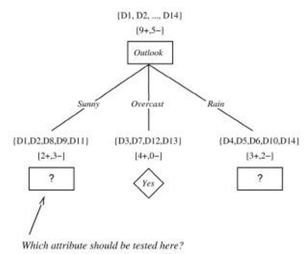
ID3 ALGORITHM

Main loop:

1. $A \leftarrow$ the "best" decision attribute for next *node*
2. Assign A as decision attribute for *node*
3. For each value of A, create new descendant of *node*
4. Sort training examples to leaf nodes
5. If training examples perfectly classified, Then STOP, Else iterate over new leaf nodes

Which attribute is the best classifier?





S_{sunny} = {D1,D2,D8,D9,D11}

$Gain(S_{sunny}, Humidity) = .970 - (3/5)\,0.0 - (2/5)\,0.0 = .970$

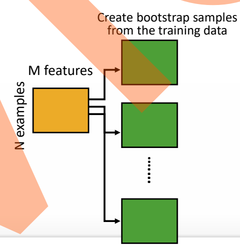
$Gain(S_{sunny}, Temperature) = .970 - (2/5)\,0.0 - (2/5)\,1.0 - (1/5)\,0.0 = .570$

$Gain(S_{sunny}, Wind) = .970 - (2/5)\,1.0 - (3/5)\,.918 = .019$

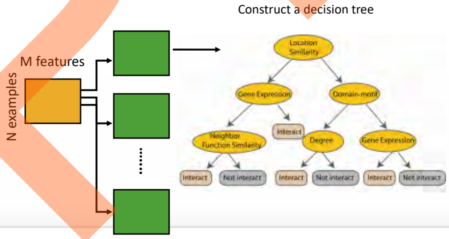
BUT: OVERFITTING

- You can perfectly fit to any training data
- Two approaches:
  - Stop growing the tree when further splitting the data does not yield an improvement
  - Grow a full tree, then prune the tree, by eliminating nodes.
- But how to do this in a smart way?

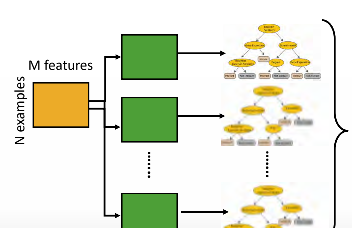
EXAMPLE WITH TREES



EXAMPLE WITH TREES

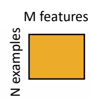


RANDOM FOREST CLASSIFIER

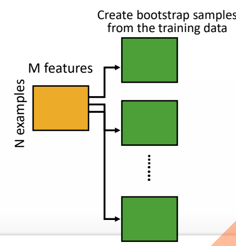


RANDOM FOREST CLASSIFIER

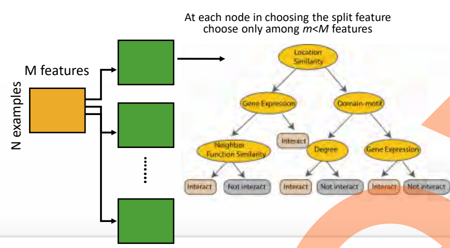
Training Data



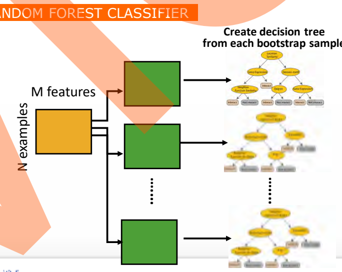
RANDOM FOREST CLASSIFIER



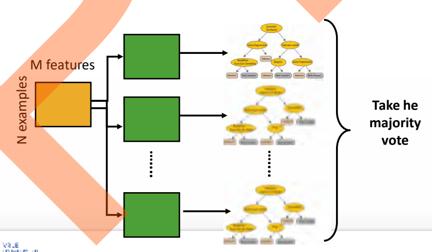
RANDOM FOREST CLASSIFIER



RANDOM FOREST CLASSIFIER



RANDOM FOREST CLASSIFIER



7 Working sessions

7.1 Exercise 1: Exploratory Data Analysis and DATA Preparation

7.2 Exercise 2: Linear regression

7.3 Exercise 3: Support vector machines

7.4 Exercise 4: Decision trees

7.5 Exercise 5: Ensemble methods

7.6 Exercise 6: Unsupervised learning k-means

7.7 Additional information, slides, articles

EXPLORATORY DATA ANALYSIS AND DATA PREPARATION

Exercise session 1

MACHINE LEARNING PROJECT CHECKLIST*

1. Frame the problem.
2. Get the data.
3. Explore the data to gain insights.
4. Prepare the data to better expose the underlying data patterns to Machine Learning algorithms.
5. Explore many different models and shortlist the best ones.
6. Fine-tune your models and combine them into a solution.
7. Present your solution.
8. Launch, monitor, and maintain your system.

*based on the Hands-on Machine Learning with Scikit-Learn, Keras, and TensorFlow by Aurélien Géron 2019

EXERCISE SESSION1: EXPLORATORY DATA ANALYSIS

Explore the Data

1. Create a copy of the data for exploration
2. Create a Jupyter notebook to keep a record of your data exploration.
3. Study each attribute and its characteristics:
   - • Name
   - • Type (categorical, int/float, bounded/unbounded, text, structured, etc.)
   - % of missing values
   - • Noisiness and type of noise (stochastic, outliers, rounding errors, etc.)
   - • Usefulness for the task
   - • Type of distribution (Gaussian, uniform, logarithmic, etc.)
4. For supervised learning tasks, identify the target attribute(s).
5. Visualize the data.
6. Study the correlations between attributes.
7. Identify the promising transformations you may want to apply.
8. Identify extra data that would be useful
9. Document what you have learned.

*based on the Hands-on Machine Learning with Scikit-Learn, Keras, and TensorFlow by Aurélien Géron 2019

EXERCISE SESSION1: DATA PREPARATION

Prepare the Data

1. Data cleaning:
   - • Fix or remove outliers (optional).
   - • Fill in missing values (e.g., with zero, mean, median…) or drop their rows (or columns).
2. Feature selection (optional):
   - • Drop the attributes that provide no useful information for the task.
3. Feature engineering, where appropriate:
   - • Discretize continuous features.
   - • Decompose features (e.g., categorical, date/time, etc.).
   - • Add promising transformations of features (e.g., log(x), sqrt(x), x2, etc.).
   - • Aggregate features into promising new features.
4. Feature scaling:
   - • Standardize or normalize features.

*based on the Hands-on Machine Learning with Scikit-Learn, Keras, and TensorFlow by Aurélien Géron 2019

TOOLKIT

Data science platform: https://www.anaconda.com/products/individual

Scikit-learn: machine learning in python: https://scikit-learn.org/

Data analysis and manipulation: https://pandas.pydata.org/

Scientific computing: https://numpy.org/

UNSUPERVISED LEARNING
K-MEANS

Exercise session 6

CLUSTERING RECAP

Clustering is the task of identifying similar instances and assigning them to clusters, i.e., groups of similar instances
(unsupervised!)

Clustering is used for:

- **data analysis:** when analyzing a new dataset, it is often useful to first discover clusters of similar instances, as it is often easier to analyze clusters separately
- As a **dimensionality reduction** technique: once a dataset has been clustered, it is usually possible to measure each instance's affinity with each cluster. Each instance's feature vector x can then be replaced with the vector of its cluster affinities(k dimensional). This is typically much lower dimensional than the original feature vector, but it can preserve enough information for further processing.
- **anomaly detection** (also called outlier detection): any instance that has a low affinity to all the clusters is likely to be an anomaly.
- **semi-supervised learning**: with only a few labels, you could perform clustering and propagate the labels to all the instances in the same cluster.
- To **segment an image**: by clustering pixels according to their color, then replacing each pixel's color with the mean color of its cluster, it is possible to reduce the number of different colors in the image considerably.

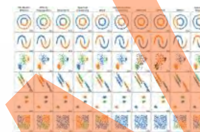


*Image is courtesy of https://scikit-learn.org/stable/modules/clustering.html

K-MEANS RECAP

The K-Means algorithm is one of the fastest clustering algorithms, but also one of the simplest:

•First initialize k centroids randomly: k distinct instances are chosen randomly from the dataset and the centroids are placed at their locations.

•Repeat until convergence (i.e., until the centroids stop moving):

- Assign each instance to the closest centroid.
- Update the centroids to be the mean of the instances that are assigned to them.

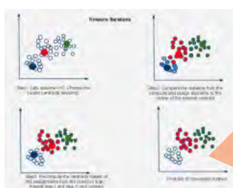


*Image is courtesy of http://humble-developer.blogspot.com/2011/01/kmeans-clustering-algorithm-part-1.html

LINEAR REGRESSION

Exercise session 2

RECAP: REGRESSION

- Regression or Classification?

Based on chemical features (alcohol, pH, chlorides…), predict the price of a wine.

Based on employee's attributes (seniority, income, department, distance from home…), predict how long until an employee looks for another job.

Based on people's attributes (level of education, area, job title, age…), predict their income.

Based on chemical features (alcohol, pH, chlorides…), predict whether a wine is red, white, or rose.

Based on space object attributes (discovery method, orbit, inclination, mass), predict whether this object is an exoplanet or not.

Based on song features (length, key, loudness, tempo…), predict a song's genre.

*examples are inspired by the course "machine learning for everyone" DataCamp

REGRESSION:RECAP

Regression: finding value of a continuous variable (target variable) based on the values of some other variables.

Classification: predicting or identifying the category a data point belongs to.

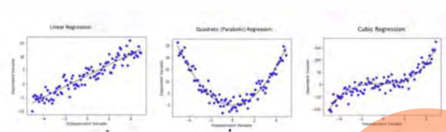
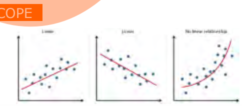


Figure source: https://medium.com/@toprak.mhmt/non-linear-regression-4de80afca347

REGRESSION EXERCISES: SCOPE

- Linear regression in scikit-learn



- Overfitting
- Regularization
- Multiple linear regression

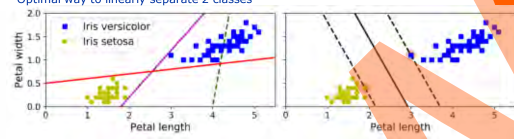
SUPPORT VECTOR MACHINES

Exercise session 3

SVM RECAP

SVM: linear or nonlinear classification, regression, outlier detection.

Optimal way to linearly separate 2 classes

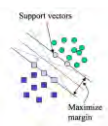


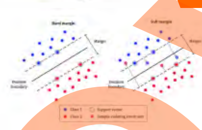
SVM: RECAP

- Optimal hyperplane for linearly separable patterns
- SVM maximizes the margin around the separating hyperplane
- The decision function is fully specified by a subset of training samples, the support vectors
- Extend to the patterns that are not linearly separableby transformations of original data to map into new space – the Kernel function

- Hard/large marging classification: sensitive to outliers, Only works for linearly separable data

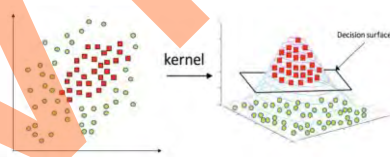
- Soft margin: Balance between keeping the margin as large as possible and limiting the margin violations





NOT LINEARLY SEPARABLE CLASSES

Kernel trick: maps non-linear input data points into higher dimension where they can be linearly separable. Kernel is a function which actually perform the mapping. Kernel types: 'linear', 'polynomial', 'radial basis function' etc.



EXPLANATION OF DATA ATTRIBUTES FROM THE REFERENCE NOTEBOOK

IRIS DATASET

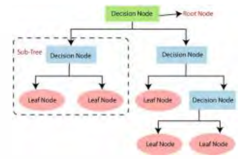
DECISION TREES

Exercise session 4

DECISION TREES

RECAP

Decision trees is a non-parametric supervised learning method, used for classification and regression.



DECISION TREES

HOW TO SPLIT?

Gini impurity

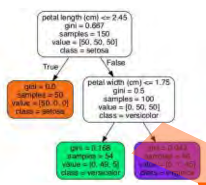
$$G_i = 1 - \sum_{k=1}^{n} p_{i,k}{}^2$$

- $p_{i,k}$ is the ratio of class k instances among the training instances in the i^{th} node.

CART algorithm

$$J(k, t_k) = \frac{m_{\text{left}}}{m} G_{\text{left}} + \frac{m_{\text{right}}}{m} G_{\text{right}}$$

where $\begin{cases} G_{\text{left/right}} \text{ measures the impurity of the left/right subset,} \\ m_{\text{left/right}} \text{ is the number of instances in the left/right subset.} \end{cases}$



DECISION TREES

RECAP

Advantages:

- simple to understand and interpret ("white box model");
- can be visualized;
- able to handle both numerical and categorical data;
- requires little data preparation;
- in-built feature selection;
- performs well with large dataset.

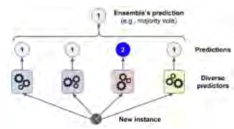
Disadvantages:

- non-robust (sensitive to the small changes in the training data);
- prone to overfitting;
- cannot guarantee to return to the globally optimal decision tree;

ENSEMBLE METHODS

Exercise session 5

ENSEMBLE METHODS



- Ensemble combines multiple individual learning models
- Individual models make differentt mistakes on the data (overfit to different parts of the data)
- Ensemble averages the mistakes

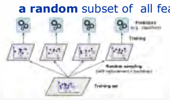
- Hard-voting: predict the class that gets the most votes
- Soft voting: average probabilities from different predictors

* Illustration from Hands-on Machine Learning with Scikit-Learn, Keras, and TensorFlow by Aurélien Géron 2019

RANDOM FOREST

- An individual Decision tree is prone to overfitting
- More decision tress -> more stable, better generalization
- Random forest = An ensemble of Decision Trees, each tree is different

- Sources of randomness:
  - Data is **randomly** split between different decision trees (bootstrapping = random selection with replacement)
  - Searches for the best feature to split at the node from **a random** subset of all features



Part 7 Intensive on campus week

- How:
  - On campus week. For a detailed planning look at the schedule on the learning platform.