# Counteracting balance loss by using wearable robotics

Speaker: Vito Monaco
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*Bari, 20 May 2019*
*Thanks to Prof. V. Bevilacqua for the invitation*

# Outline of the presentation

- **Fall risk: what are we talking about?**
- State of art
  - Assessing the fall risk
  - Detecting falls/lack or balance
  - Counteracting falls/lack of balance
- Wearable robot: the dream
- Our toolbox
  - SENLY
  - Active Pelvis Orthosis
- A possible strategy
  - Detection Algorithm
  - Assistive strategy
- Ongoing activities
  - Different perturbations
  - Other approaches for the detection
  - Robotic prosthesis
- Conclusions

# Fall risk: what are we talking about?

**Who falls**

Where/How

Consequences

How much

| Risk factor | Range | | |
|---|---|---|---|
| Age | + 65 | Fall risk (1 fall per year) | 30% |
| | + 80 | | 50% |
| Gender | M | Injury rate | F > M |
| | F | | |
| Medical Conditions | • Diabetes<br>• Parkinson's disease<br>• Depression<br>• Incontinence<br>• Alzheimer disease | | |
| Physical Conditions | • Muscle weakness<br>• Impaired balance<br>• Gait deficits<br>• Visual deficits | • Limited mobility<br>• Cognitive impairments<br>• Impaired ADL<br>• Postural Hypothension | |
| Behavioral factors | • Sedentary lifestyle<br>• Medication intake<br>• Alcohol misuse<br>• Inappropriate shoes | | |

*A global report on falls prevention - WHO*

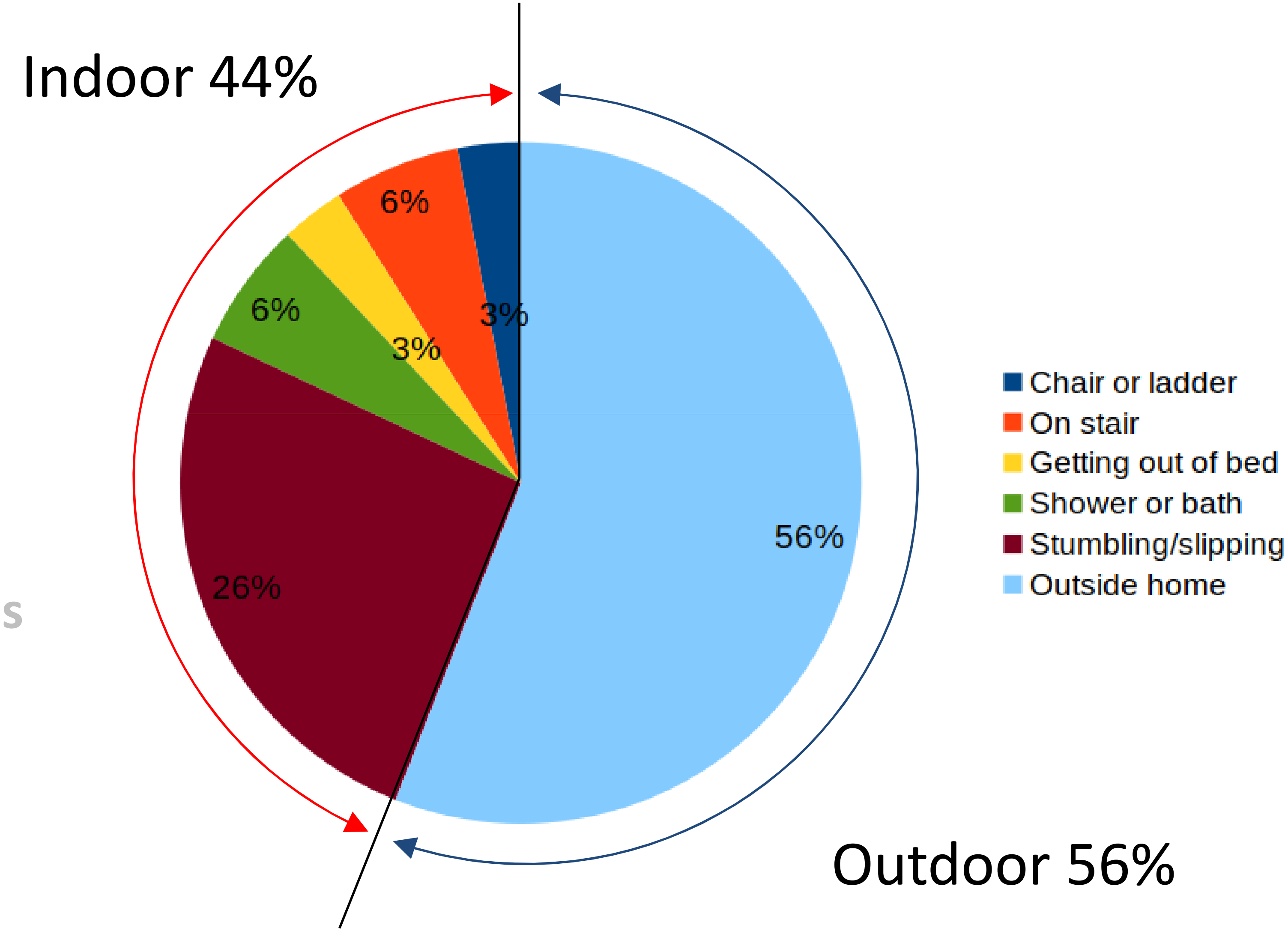
# Fall risk: what are we talking about?

Who falls

**Where/How**

Consequences

How much




*A global report on falls prevention - WHO*

# Fall risk: what are we talking about?

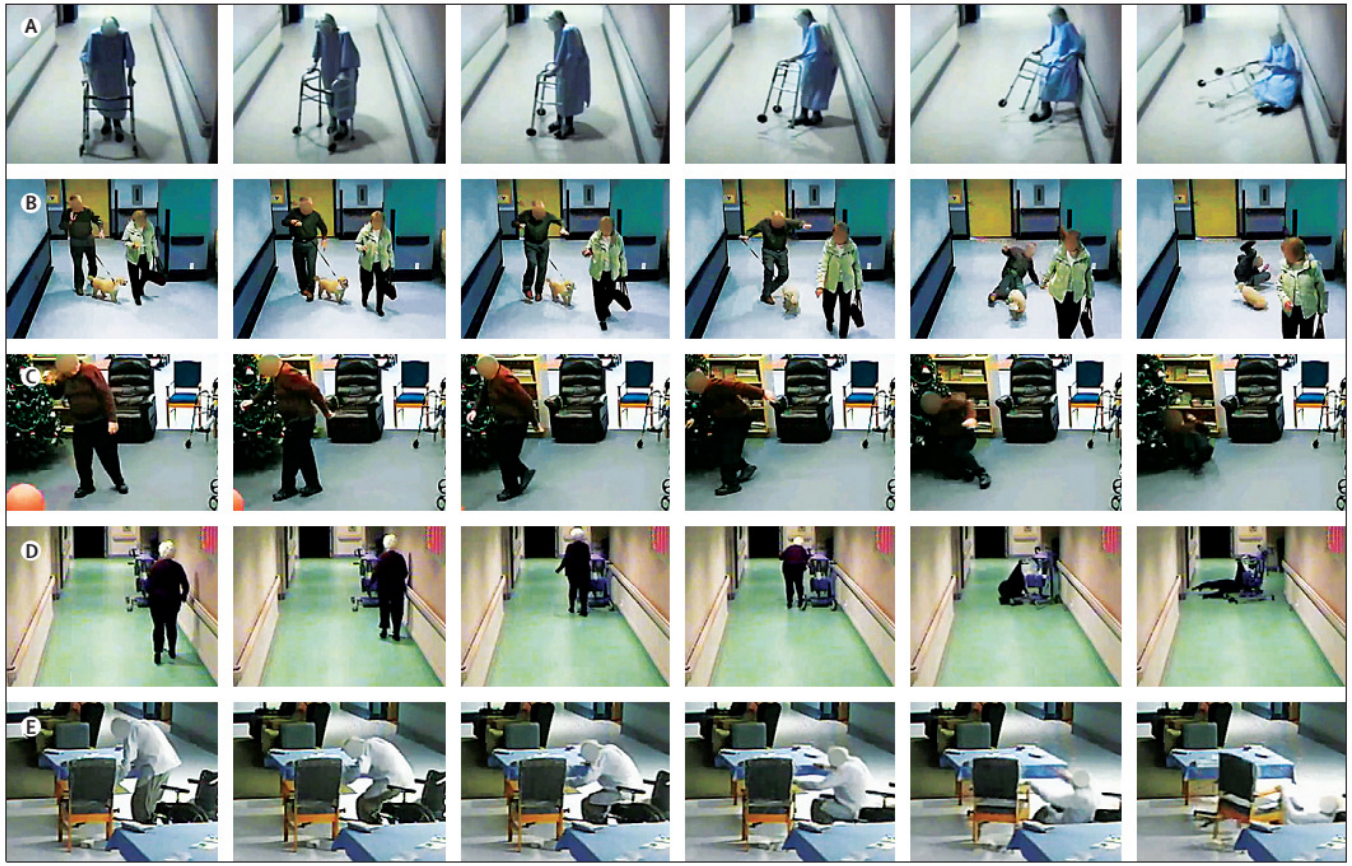
Who falls

**Where/How**

Consequences

How much

Video capture of the circumstances of falls in elderly people residing in long-term care: an observational study




*Robinovitch et al., Lancet 2013*

# Fall risk: what are we talking about?

Who falls

**Where/How**

Consequences

How much

Video capture of the circumstances of falls in elderly people residing in long-term care: an observational study

Estimated proportion of participants falling at least once, and average number of falls per participant, attributable to various causes of falling

| | Frequency* | | Participants falling due to this cause† | | Number of falls per participant† | |
|---|---|---|---|---|---|---|
| | Number | Percentage of falls captured | Estimated proportion, % (SE) | 95% CI | Estimated count, n (SE) | 95% CI |
| Incorrect transfer or shift of bodyweight | 93 | 41% | 51·2% (4·5) | 42·5–59·8 | 0·72 (0·078) | 0·59–0·90 |
| Trip or stumble | 48 | 21% | 26·0% (3·9) | 19·1–34·3 | 0·35 (0·054) | 0·26–0·47 |
| Hit or bump | 25 | 11% | 17·3% (3·4) | 11·7–25·0 | 0·19 (0·040) | 0·13–0·28 |
| Loss of support with external object | 25 | 11% | 18·9% (3·5) | 13·0–26·7 | 0·20 (0·041) | 0·13–0·30 |
| Collapse or loss of consciousness | 24 | 11% | 16·5% (3·3) | 11·0–24·1 | 0·17 (0·039) | 0·11–0·27 |
| Slip | 6 | 3% | 4·7% (1·9) | 2·1–10·2 | 0·047 (0·020) | 0·021–0·11 |
| Could not tell | 6 | 3% | ·· | ·· | ·· | ·· |

In descending order of frequency.

*Of 227 total falls captured.

†Of 215 falls analysed, after exclusion of cases for which the faller could not be identified (six), and cases for which the team could not identify the cause of the fall (six).

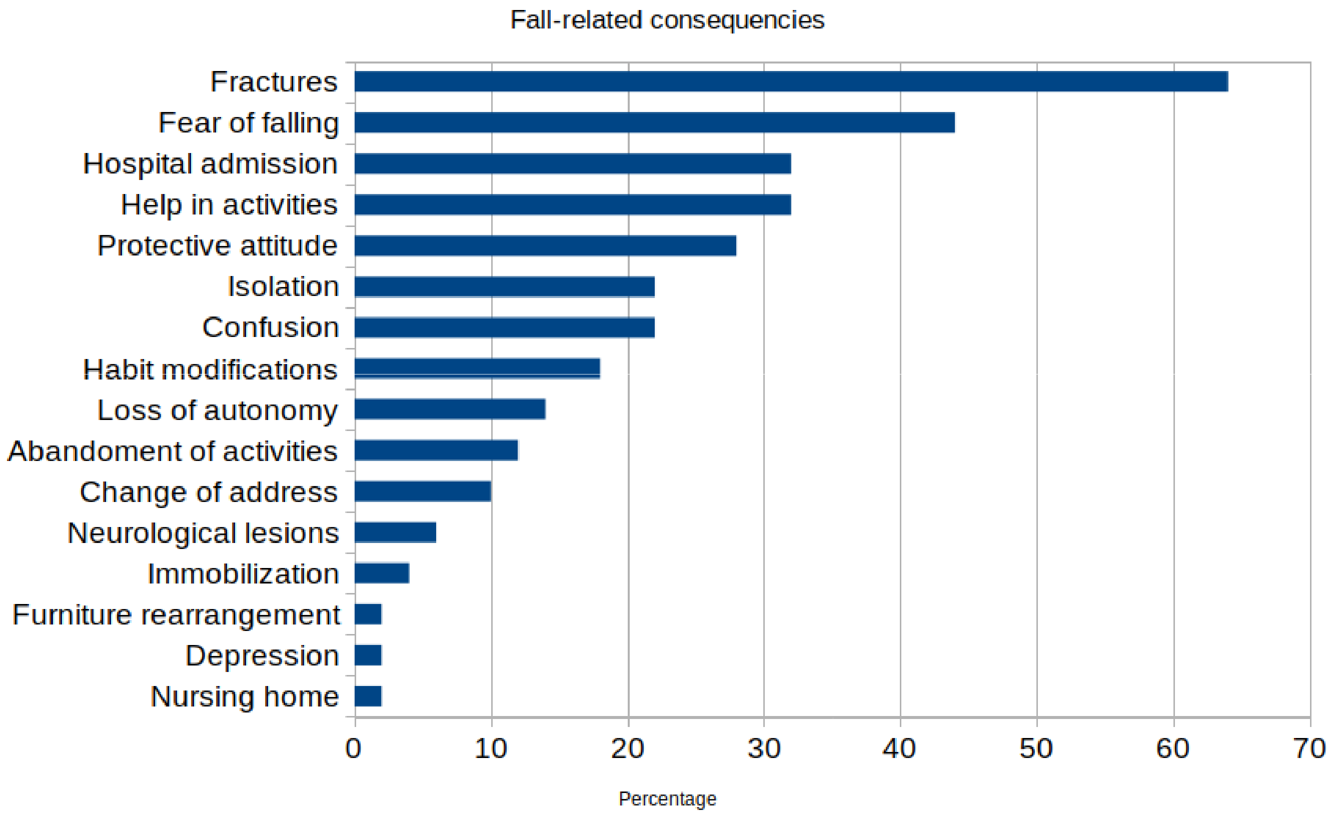
*Robinovitch et al., Lancet 2013*

# Fall risk: what are we talking about?

Who falls

Where/How

**Consequences**




How much

*A global report on falls prevention - WHO*

# Fall risk: what are we talking about?

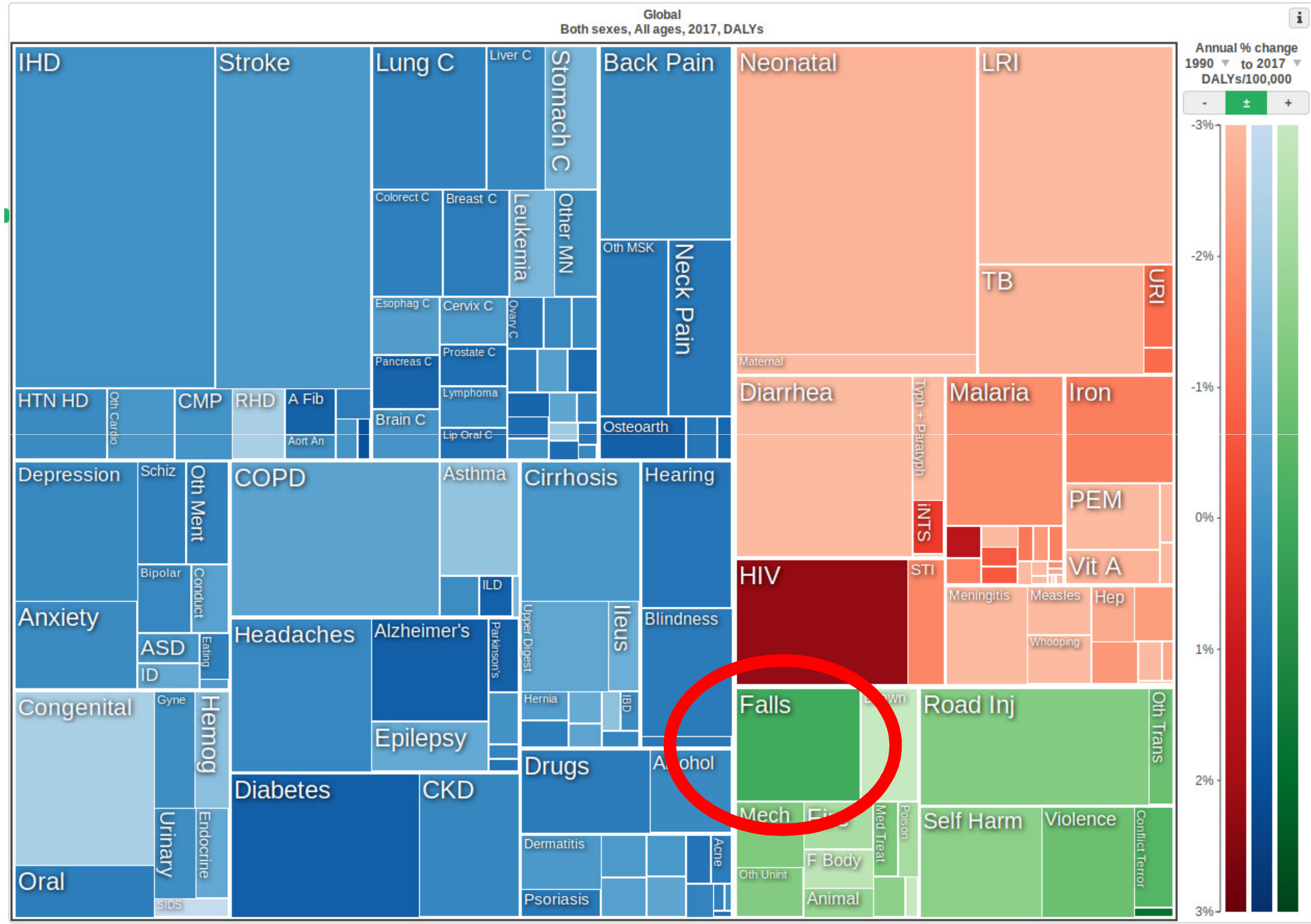
Who falls

Where/How

Consequences

**How much**

Global Burden of Disease




DALYs ~ the number of years lost due to the ill-health, disability, or early death

*https://vizhub.healthdata.org/gbd-compare/*

# Fall risk: what are we talking about?

Who falls

Where/How

Consequences

**How much**

- Fall-related injuries are among the most expensive health conditions
- In 2000, $179 million were spent on fatal falls and $19 billion were spent on injuries from non-fatal falls in US

*Stevens et al., Inj. Prev. 2006*

- Modena University Hospital 2012
  - 220/240 hip fracture per year
  - € 10.000 per fracture
    - € 2.2-2.4 million per year
- Italy: € 1 billion per year due to falls
- Europe: € 800 billion per year due to falls

*Dr. La Porta, SIAMOC 2018*

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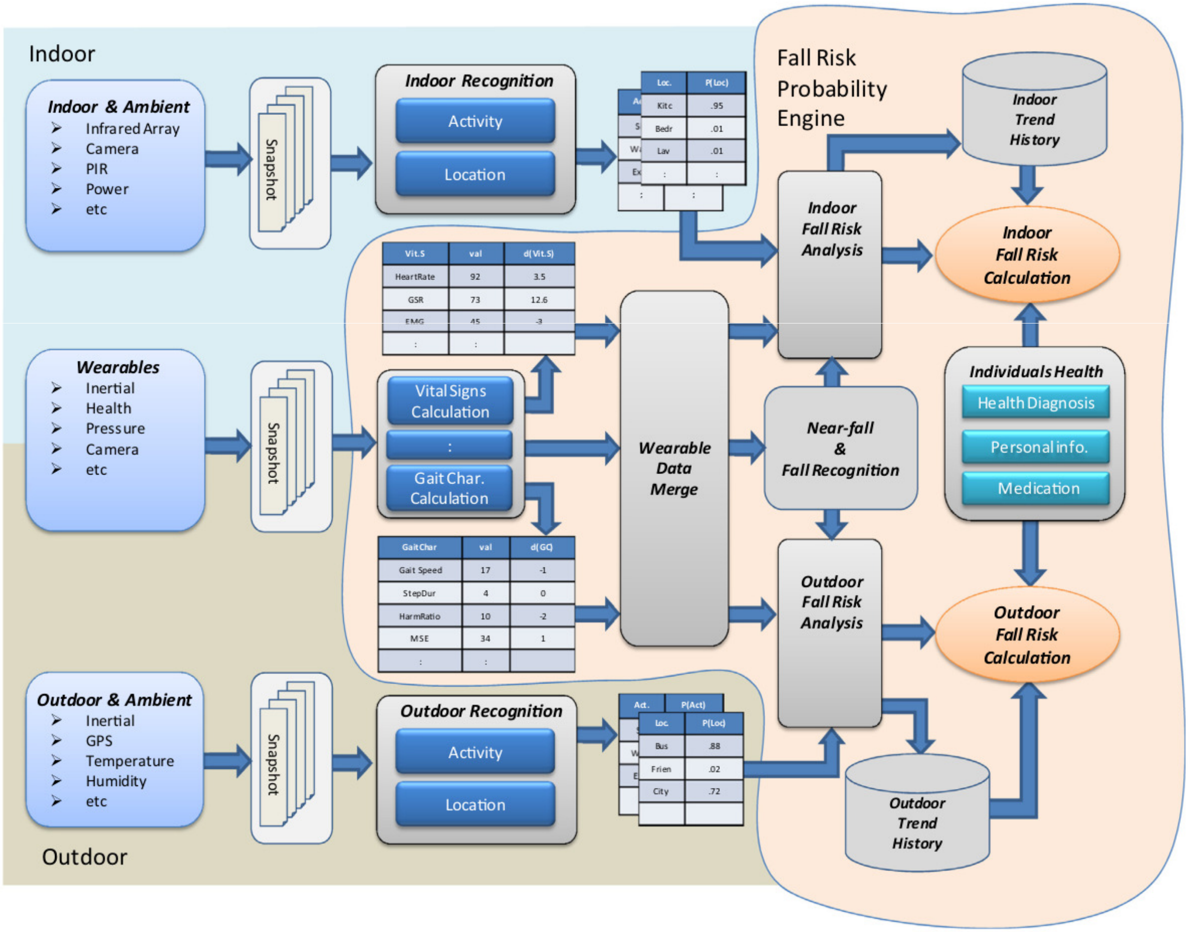
# Assessing the fall risk

*Fall risk assessment is a process in which the probability of a future fall is estimated, usually within a timeframe of 6–12 months.*



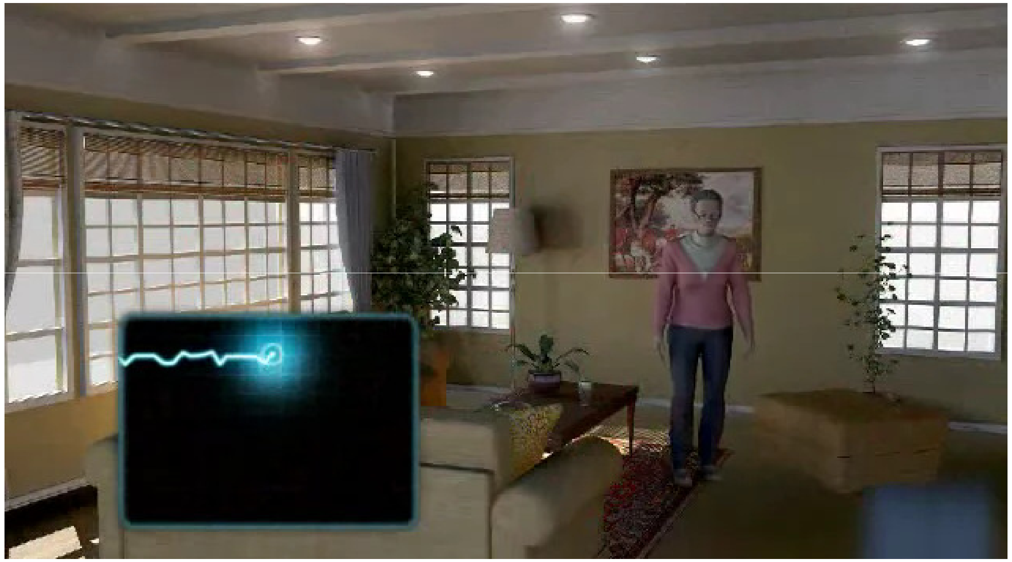

*Danielsen et al., J Biom. Inf. 2016*

# Detecting falls

## Personal Emergency Report System (PERS 2.0)

- **How it works**
  - Devices able to detect a fall <u>after it occurs</u> in order to overcome long-lie conditions;
  - Based on smart environments, video-cameras, acoustic or inertial sensors, and mobile phone technology.
- **Limits**
  - Able to detect a fall only after the subject hits the ground
  - Some of them only work in structured environments
- **Commercially available**

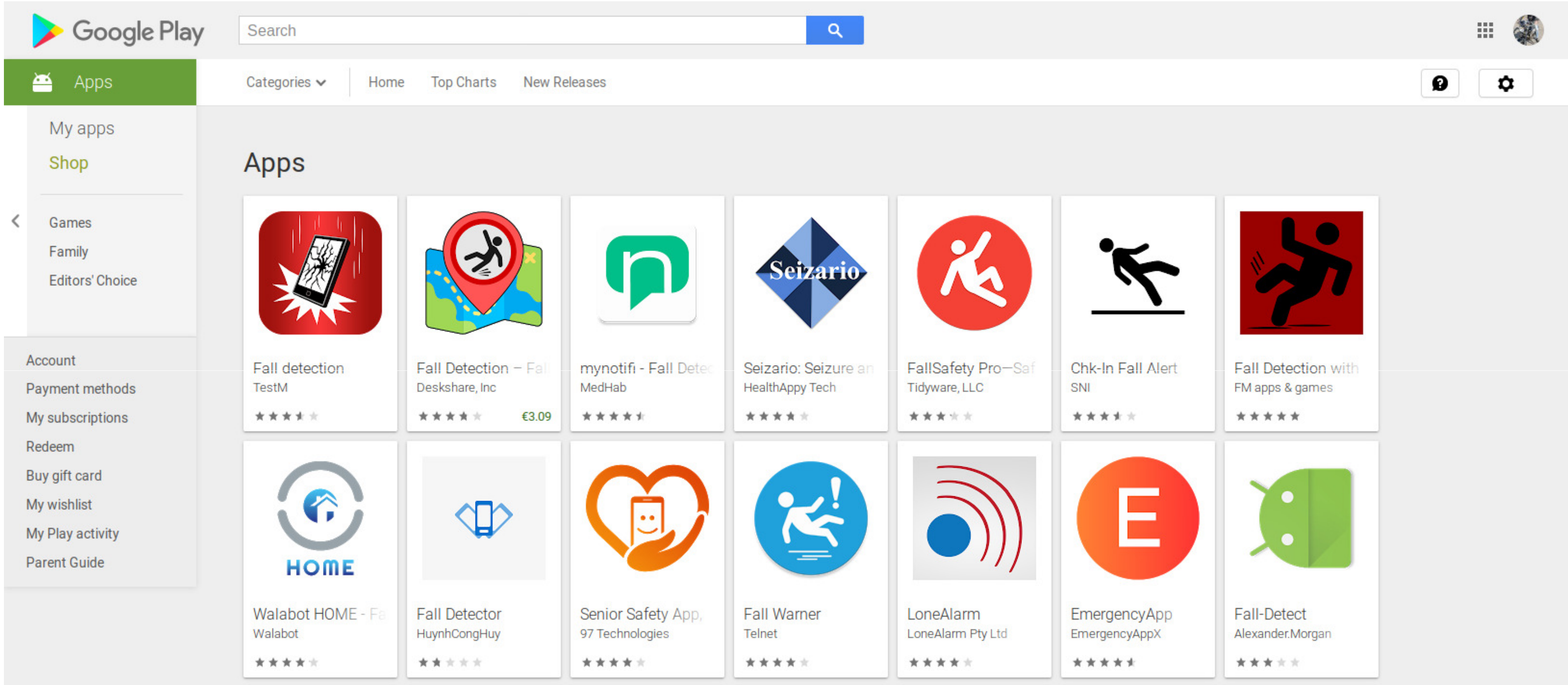
Wearable sensors



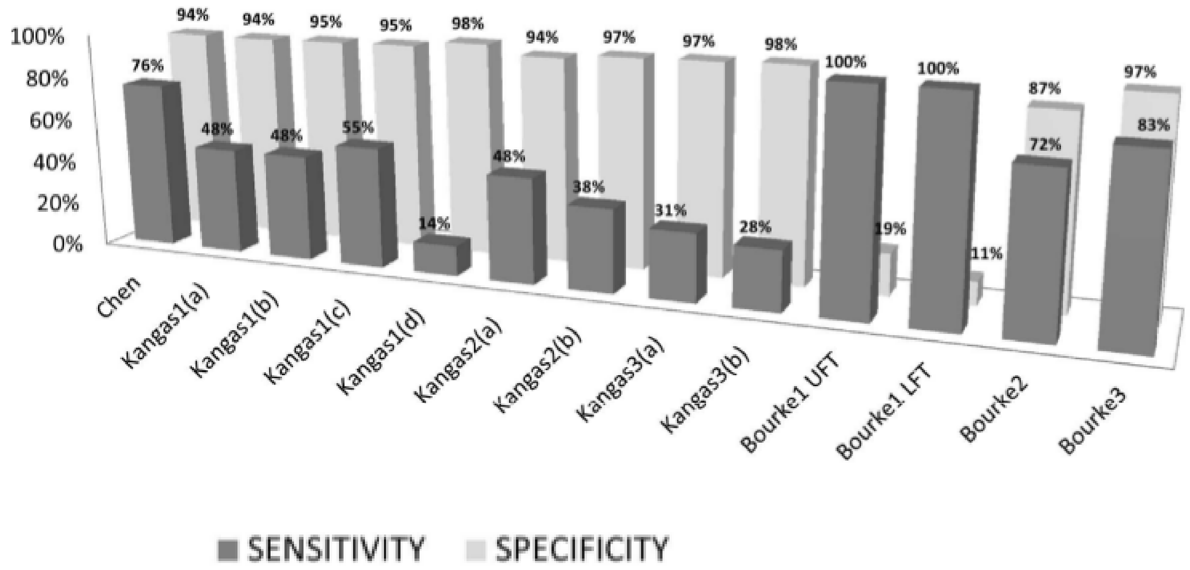


myHalo® Auto Fall Detect Pendant by MobileHelp®

# Detecting falls



# Detecting falls: do current algorithms work in the real world?



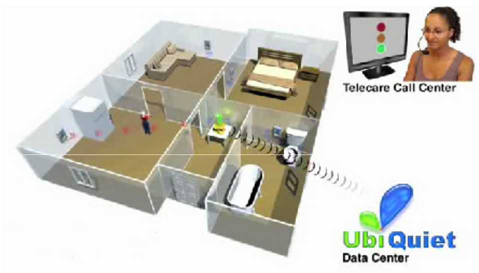

Algorithms
- tuned on simulated falls
- tested on real falls

**Algorithms based on simulated data do not work very well in the real World**

- **Sensitivity** measures the proportion of actual positives which are correctly identified
- **Specificity** measures the proportion of negatives which are correctly identified

*Bagalà et al., PLOSOne 2012*

# Detecting falls

| | Pros | Cons |
|---|---|---|
| **Sensorized Environments**   | • Many sensors<br>• Mitigate fall consequences (“long lie”)<br>• Autonomous | • Structured Environments<br>• Invasive<br>• Act after falling |
| **Wearable Sensors**  | • Unstructured Environments<br>• Embedded in personal devices | • Not reliable set-up<br>• Non Autonomous |

# Pre-impact fall detection


## Lack of balance ≠ fall

- <u>Falling</u>: lying on the ground after hitting it
- <u>Lack of balance</u>: maybe, you can still recovery the balance… maybe not

- Pros
  - to timely ask for assistance
  - to timely activate fall protection systems
- Weaknesses
  - data collected in structured environments
  - protection system: any suggestion?

*Hu and Qu, BioMed Eng Online 2016*

# Pre-impact fall detection

## Experimental sessions

- Pros
  - to timely ask for assistance
  - to timely activate fall protection systems
- **Weaknesses**
  - **data collected in structured environments**
  - protection system: any suggestion?

*Hu and Qu, BioMed Eng Online 2016*

# Pre-impact fall detection

## Protection systems

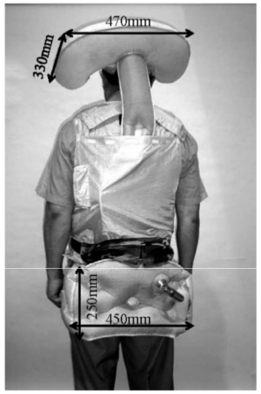
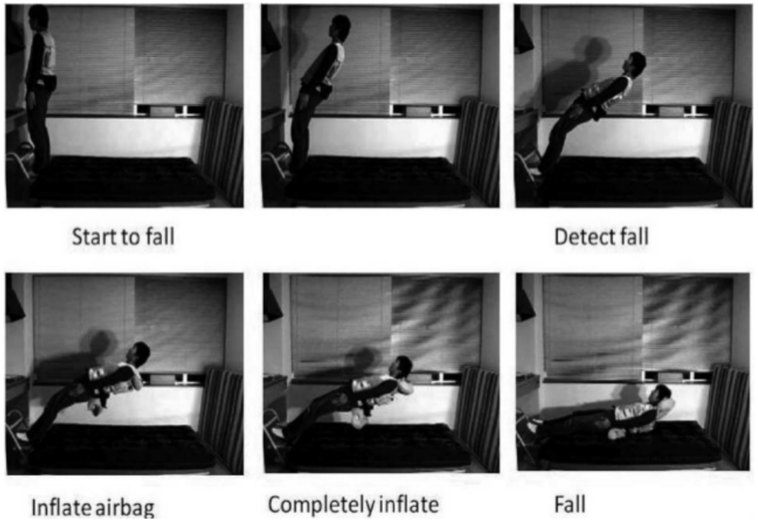



TABLE II
INFLATION TIME OF THE AIRBAG WHILE MIMICKING A FALL USING THE PROPOSED ALGORITHM

| Subjects | Inflation time | Fall time |
|---|---|---|
| 1 | 0.100 | 0.207 |
| 2 | 0.140 | 0.387 |
| 3 | 0.133 | 0.223 |
| 4 | 0.121 | 0.177 |
| Ave | 0.121 | 0.249 |
| SE | 0.019 | 0.094 |




- Pros
  - to timely ask for assistance
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- **Weaknesses**
  - data collected in structured environments
  - **protection system: any suggestion?**

*Tamura et al., IEEE TITB 2009*

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# Wearable robots: the dream

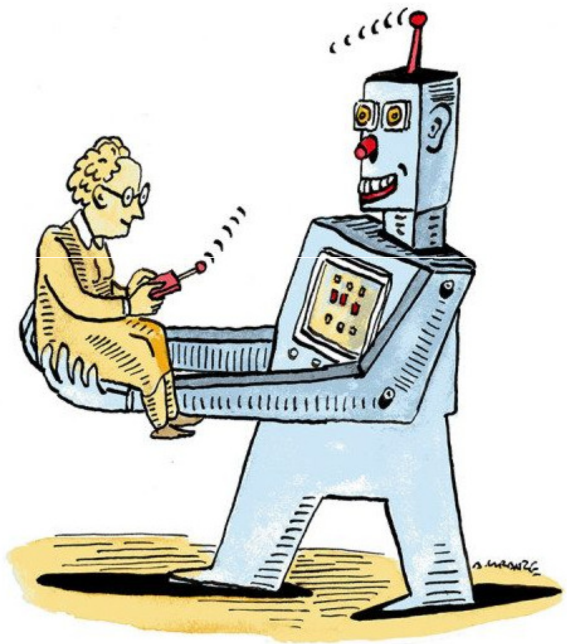
*"Perhaps in the latter half of this century, exoskeletons and orthoses will be as pervasive in society as wheeled vehicles are today."*

*Herr, JNER 2009*

# Why robots against falls?

Wearable robots are:

- equipped with <u>sensors</u> to monitor subjects' dynamical conditions
- equipped with <u>actuators</u> to modify user's dynamical balance
- controllable/programmable
- <u>multiple purposes</u> platforms
- active before falling
    - not hitting the ground
    - not stigmatizing the balance loss

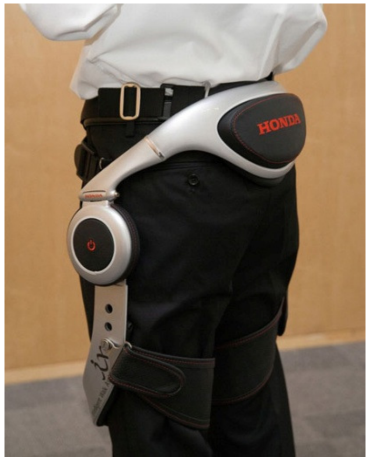


# Wearable robots: the dream

HAL5
[Cyberdyne]

Hyundai Exoskeleton
[Hyundai Motor]

Rewalk
[Argo]




Body weight support
[Honda]

HAL Lumbar for labor support
[Cyberdyne]

HAL Lumbar for care support
[Cyberdyne]

# Wearable robots

| | What they do |
|---|---|
| Full body exoskeletons  | not currently used in daily-life scenarios except for strongly motivated persons affected by severe diseases (e.g., young patients affected by spinal cord injury resulting after a traumatic accident) |
| Pelvis exoskeletons  | **Can these be used to counteract the lack of balance?** |

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# Our experimental setup: SENLY

TERRINet
The European Robotics
Research Infrastucture Network

Transnational access – **free of charge** –
to research infrastructures

Main features:

- size 2.5m x 2.5m
- double split treadmill
- AP belt movement
  - max speed 1.8 m/s
  - max acc 8 $m/s^2$
- ML belt movement
  - max disp 0.3 m
  - max speed 1.25 m
  - max acc 2.4 $m/s^2$
- Sensorized platform

*Bassi Luciani et al., JNER 2012*

# Modulating the intensity of the perturbation

Onset: HS of the limb being perturbed

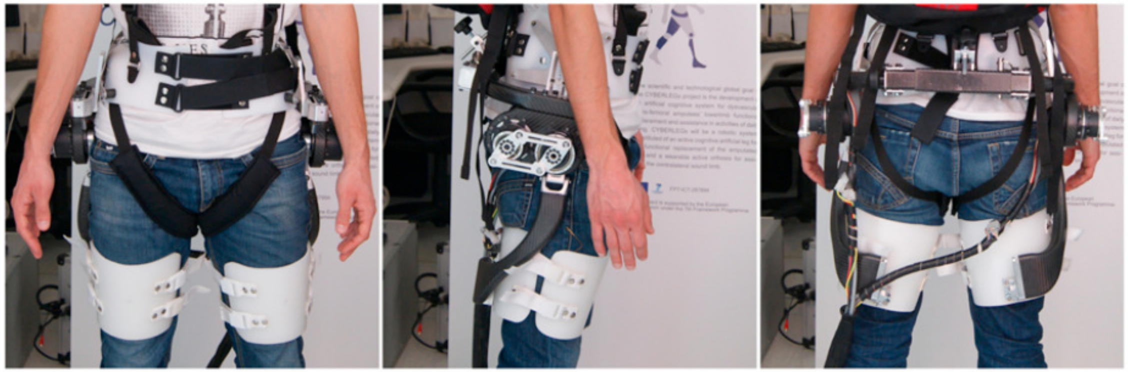
Onset: TO of the contralateral limb

HS

TO

*Bassi Luciani et al., JNER 2012*

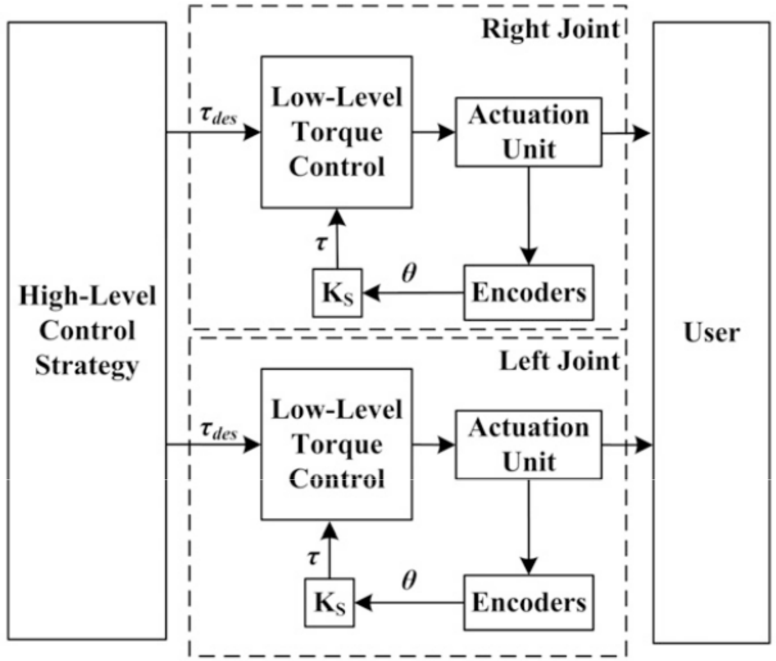
# Active Pelvis Orthosis (APO)

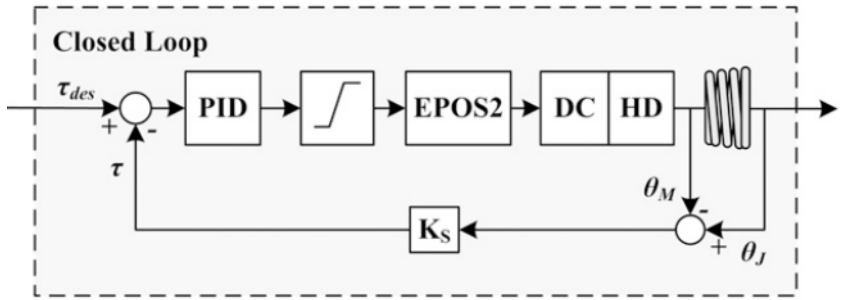


| Active and Passive degrees of freedom | | |
|---|---|---|
| Active flexion/extension RoM | Extension: -30 deg | Flexion: 110 deg |
| Passive abduction/adduction RoM | Adduction: -15 deg | Abduction: 45 deg |
| **SEA Characteristics** | | |
| Motors | 100 W BL DC Maxon Motor | |
| Reduction Stage | 100:1 Harmonic Drive | |
| Spring Stiffness | 100 Nm/rad | |
| **SEA Performance** | | |
| Max torque | Continuous: 20 Nm | Peak: 35 Nm |
| Joint output mechanical impedance | < 1 Nm/rad @ 1 Hz | |
| Closed-loop torque-control bandwidth | 15 Hz | |
| **Control Architecture Characteristics** | | |
| Low-level controller sampling rate | 1 kHz | |
| High-level controller sampling rate | 1 kHz | |
| **Others** | | |
| Weight | 4.2 kg | |
| Safety limits | Active DoF out of RoM | Joint speed > 400 deg/s |
| Power Supply | 48 V | |

*Giovacchini et al., Rob and Aut Sys 2015*

# Active Pelvis Orthosis (APO)


*Giovacchini et al., Rob and Aut Sys 2015*

# Active Pelvis Orthosis (APO)

α-prototype

β-prototype

γ-prototype

SPIN Off

Impresa Spin-Off della Scuola Sant'Anna

IUVO

www.iuvo.company

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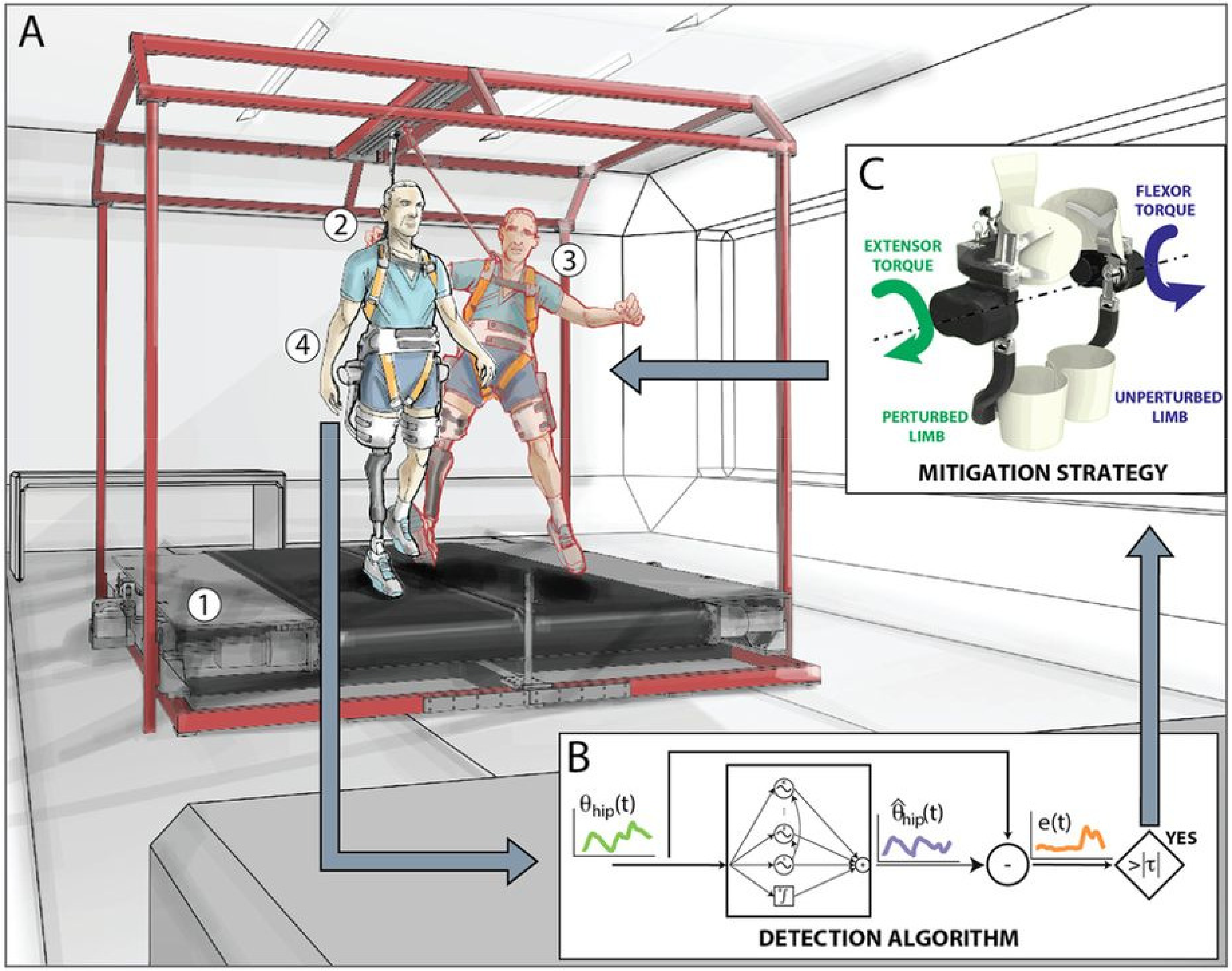
# Overview of the proposed strategy




*Monaco et al., Sci Rep 2017*

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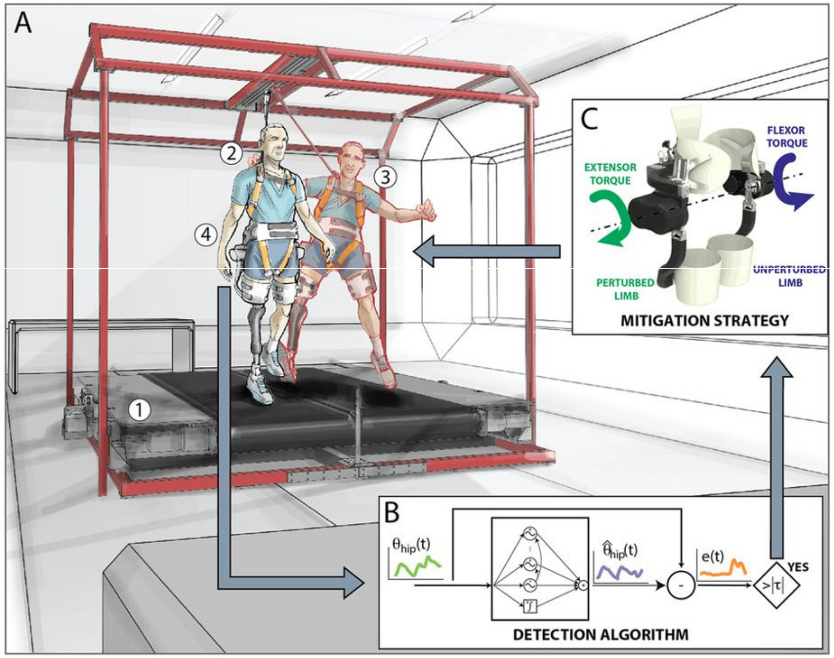
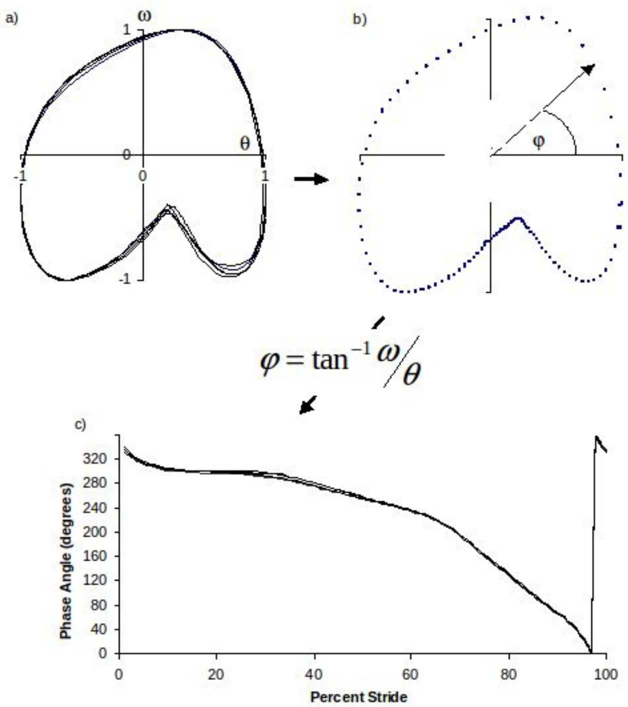


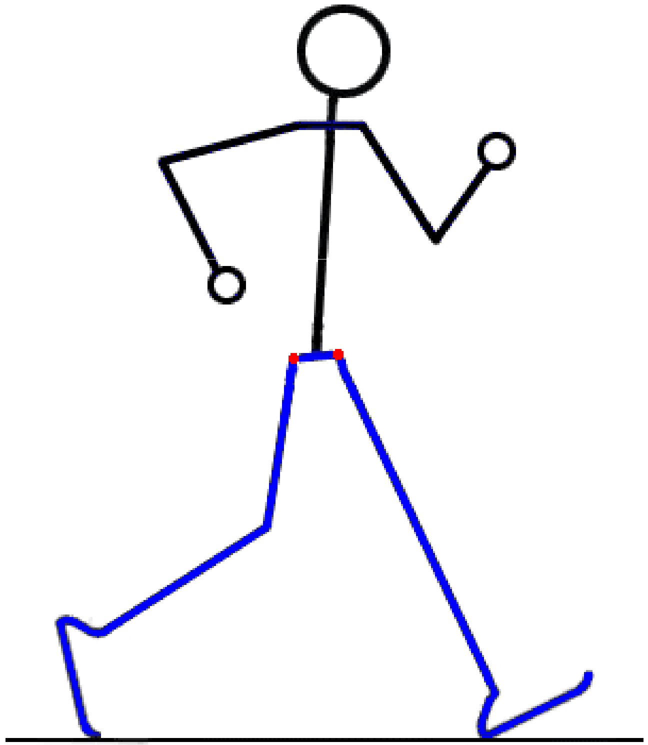

Main issues:

1. Detecting the lack of balance
   - How to do
   - Is it feasible?
   - Is it "on time"?
2. Counteracting the lack of balance
   - How to do
   - Is it effective?
3. Any other approach?

# Detecting the lack of balance

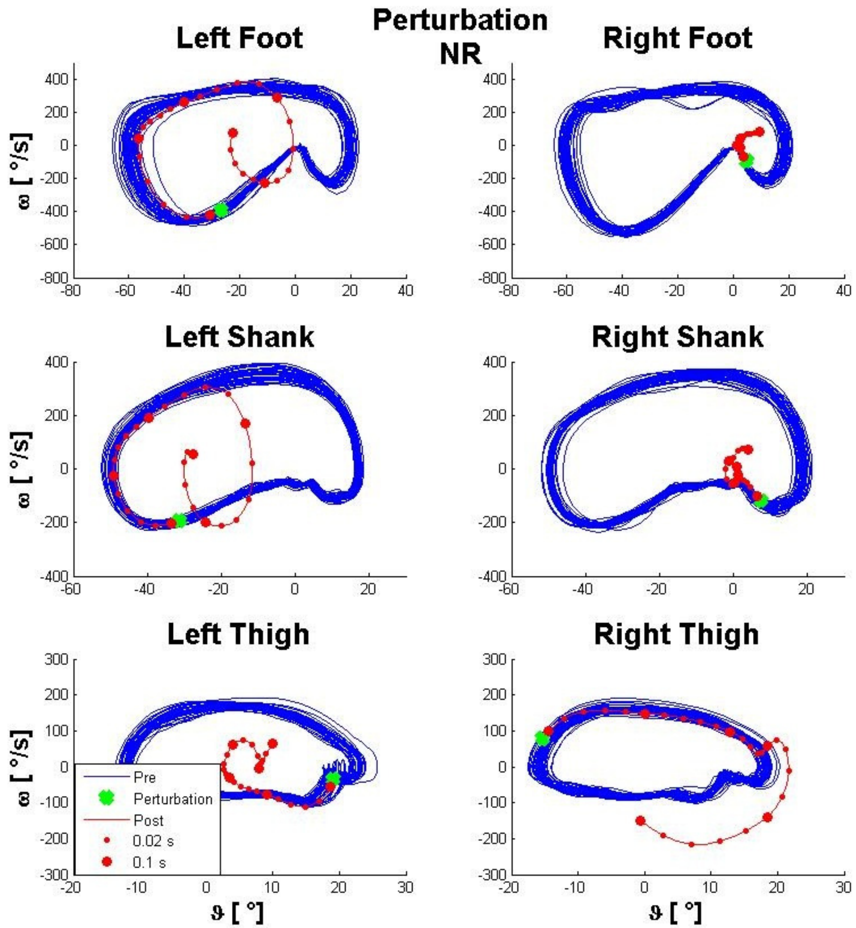
*Human walking can be considered a quasi automatic and periodic motor task whose features can be described by suitable attractors and/or limit cycles reflecting strong intra-limb and inter-limbs coordination*

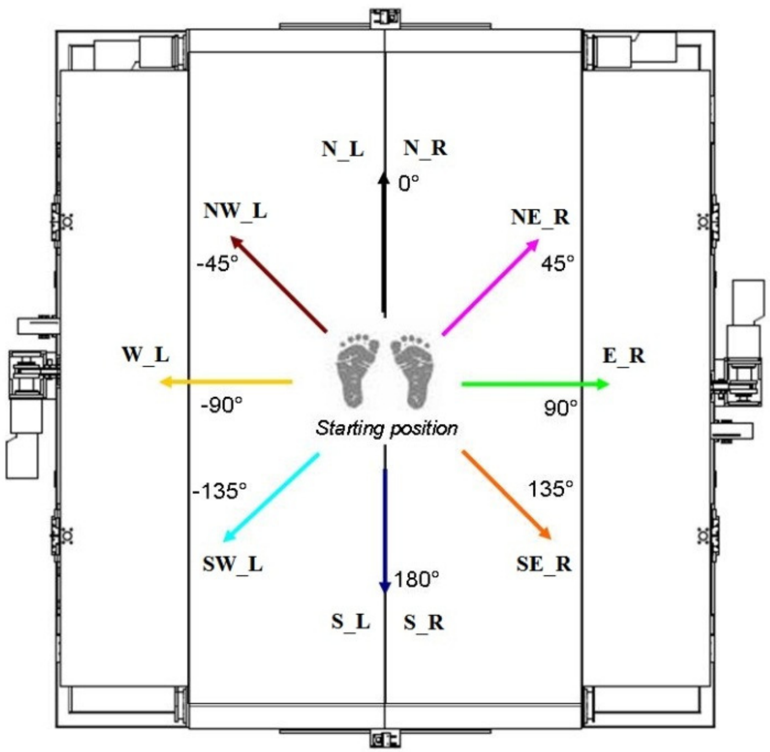


# Detecting the lack of balance

*When the dynamics of the locomotion is altered by a sudden and unexpected perturbation, intra- and inter-limbs coordination is modified and their rhythmic features are lost*



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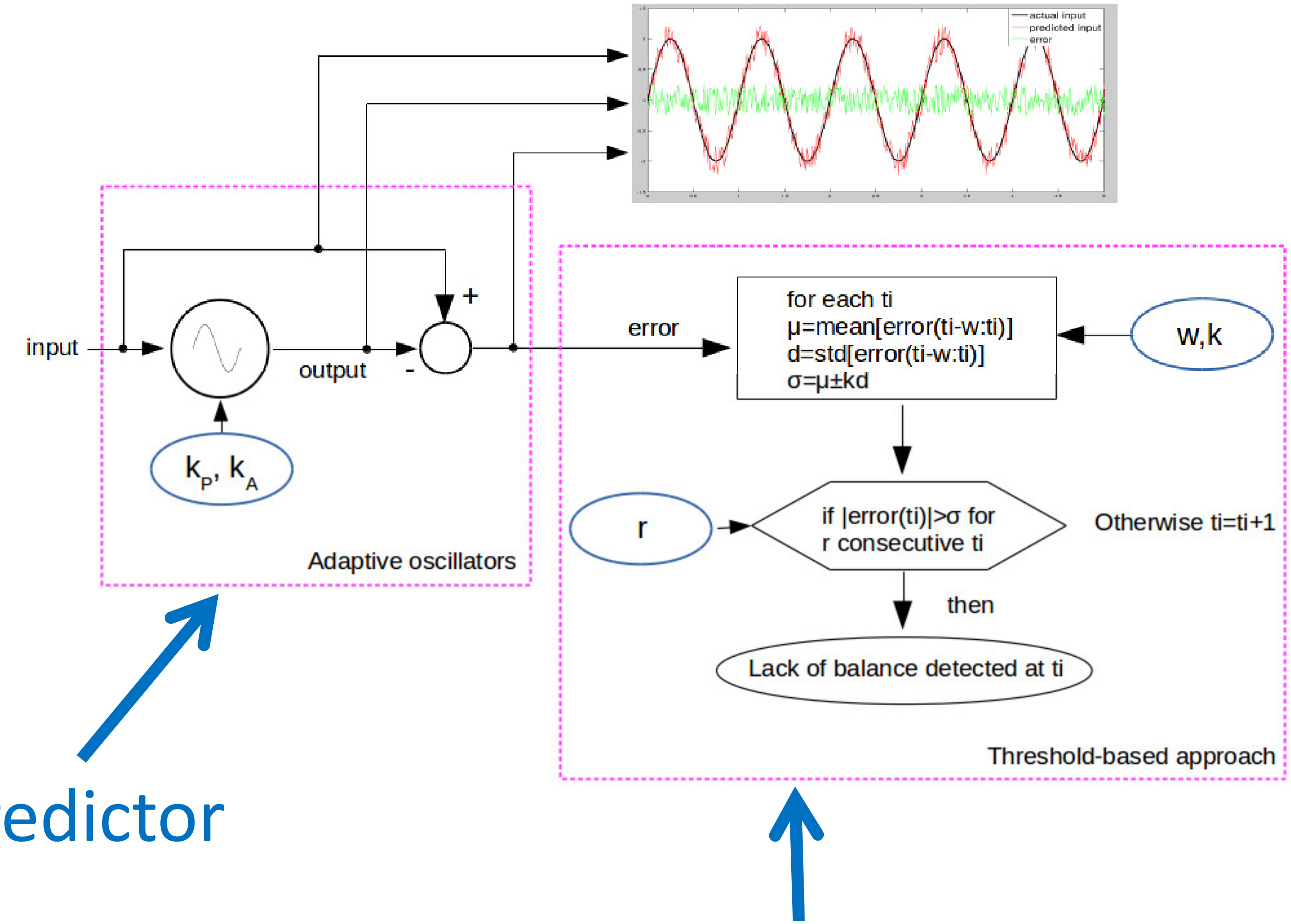


Predictor

Threshold-based algorithm

*Tropea et al., Ann Biom Eng 2014*

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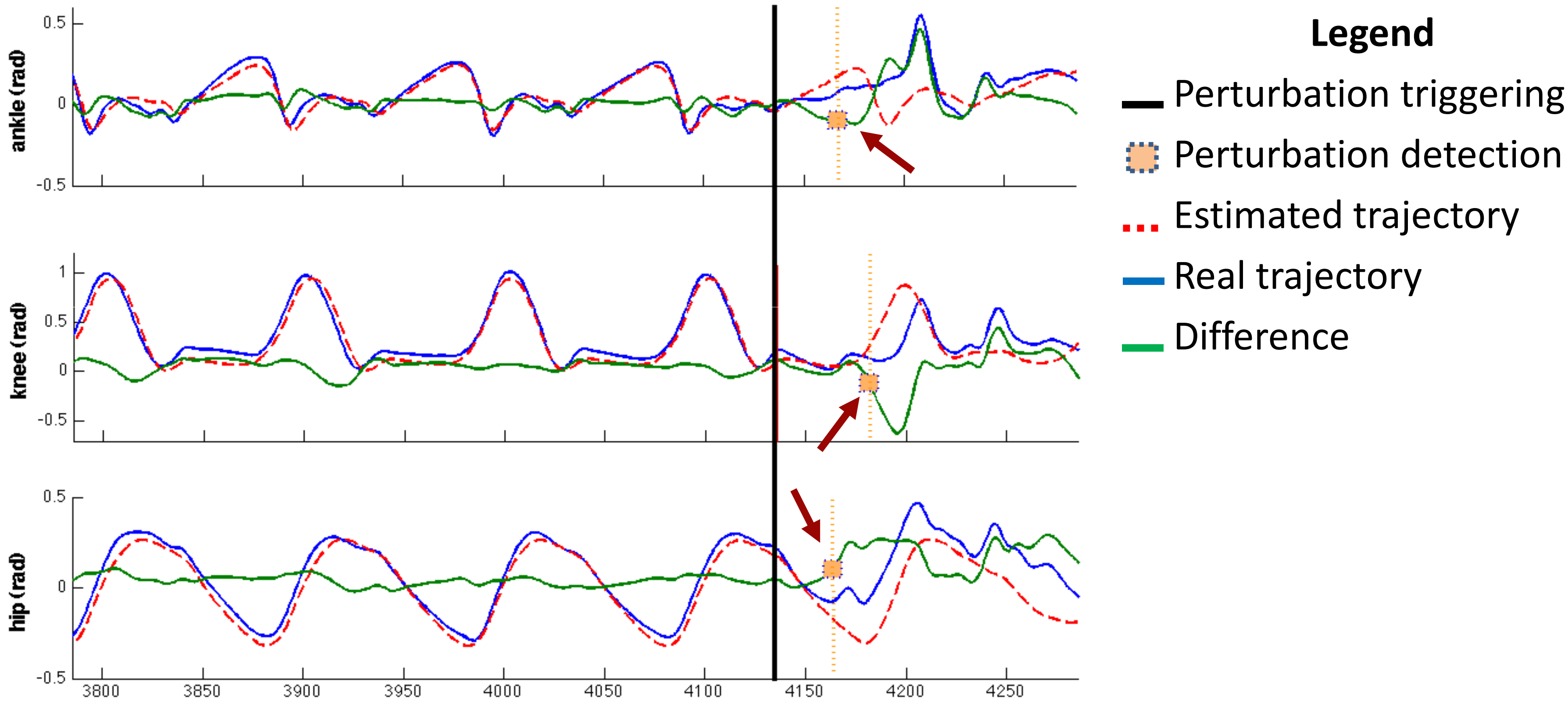


*Tropea et al., Ann Biom Eng 2014*

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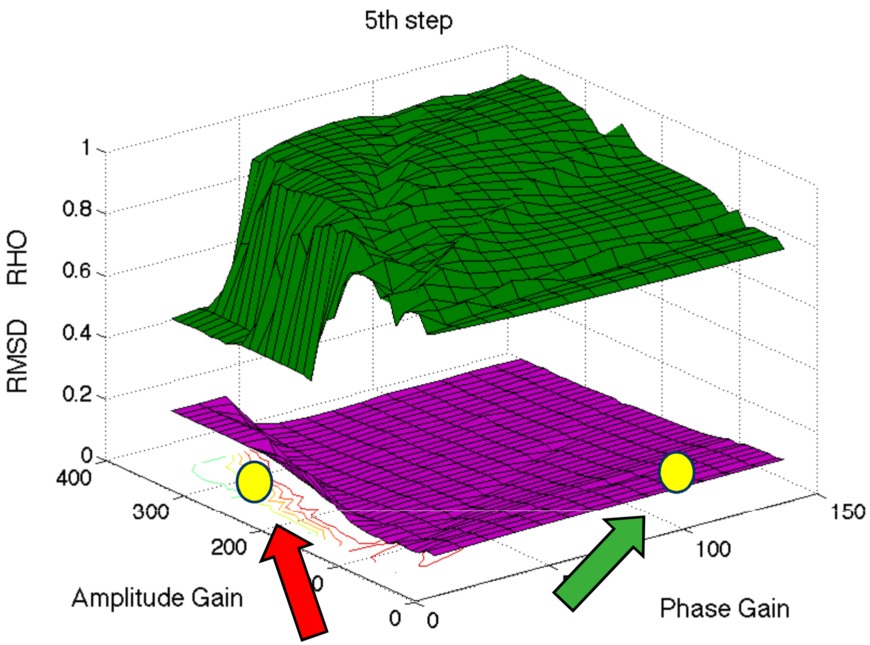
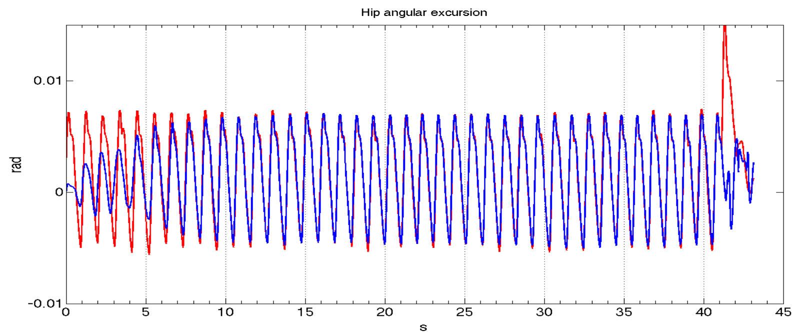
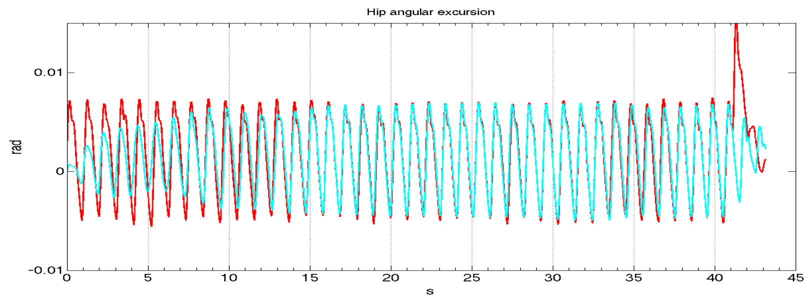
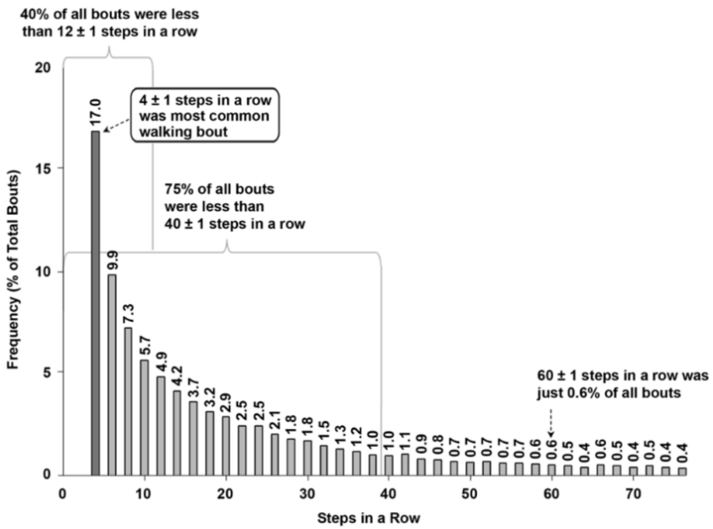



**GOOD**




**BAD**




*Tropea et al., Ann Biom Eng 2014*

*Orendduff et al., JRRD 2008*

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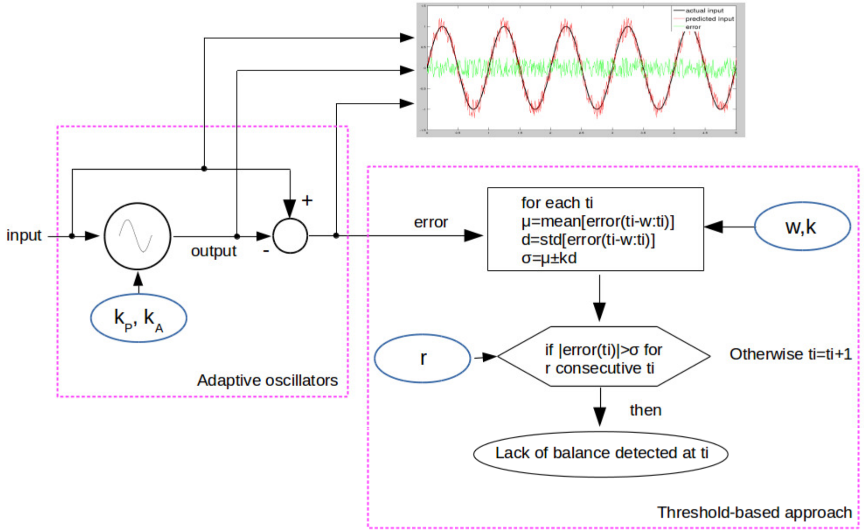
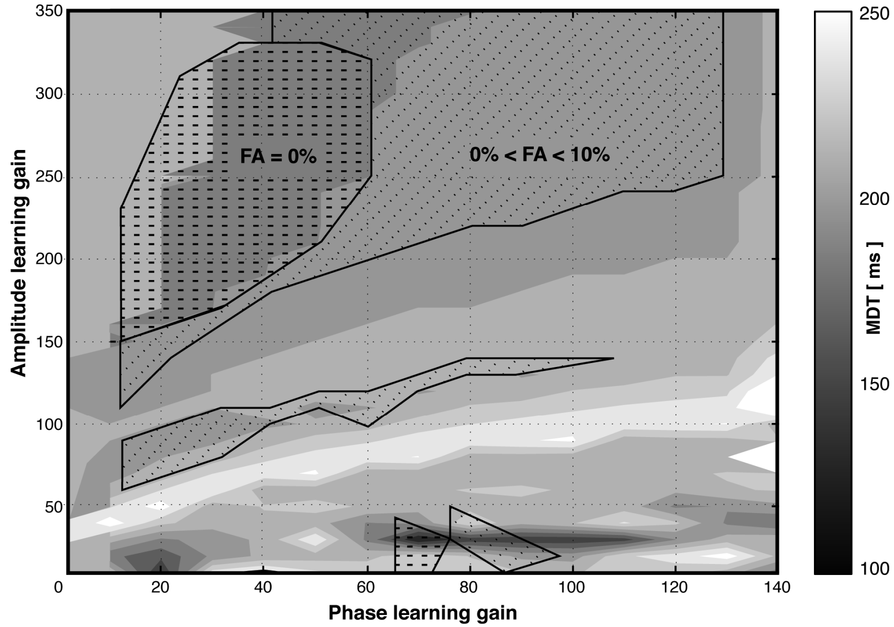



Optimal tuning:

- min detection time
- min false alarms
- short transitory (4/5 strides)

perturbed hip w = 100 r = 4 k=3




Tuning parameters:

- $k_A$ and $k_P$, amplitude and phase gains
- $w$, bin length
- $k\sigma$, threshold
- $r$, # warning

*Tropea et al., Ann Biom Eng 2014*

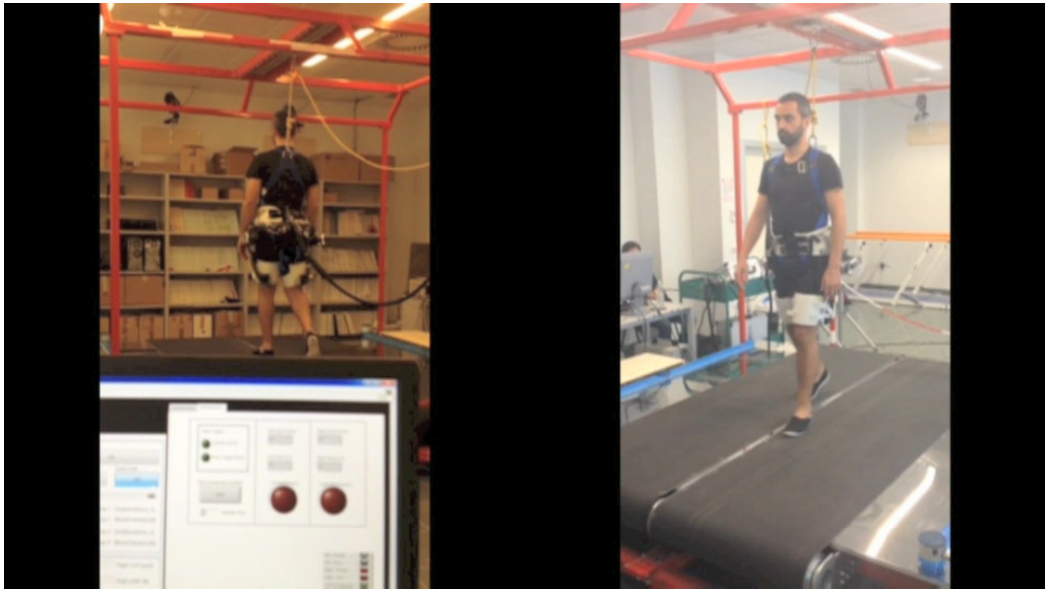
# Detecting the lack of balance

## Results

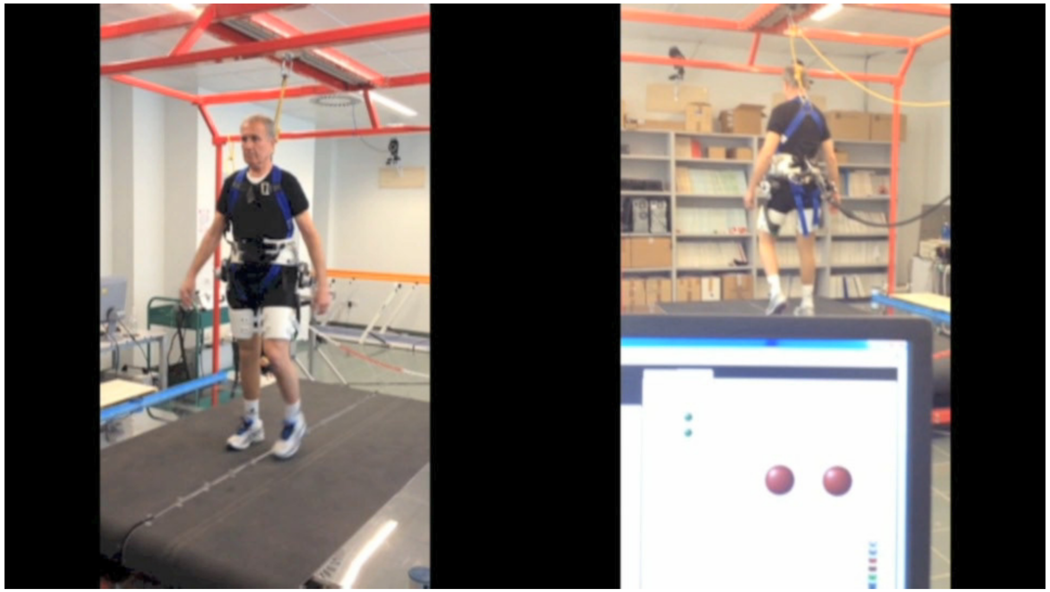
### Best adaptive oscillator performances

| Hip joint angular excursion | | | |
|---|---|---|---|
| Protocol | Accuracy [%] | Value [ms] | Strides |
| HS | 91.7 | 289 ± 81 | 5 |
| TO | 88.2 | 166 ± 12 | 5 |

# Detecting the lack of balance



WLK Speed = 1.1 m/s
MDT = 291 ms



WLK Speed = 0.64 m/s
MDT = 403 ms

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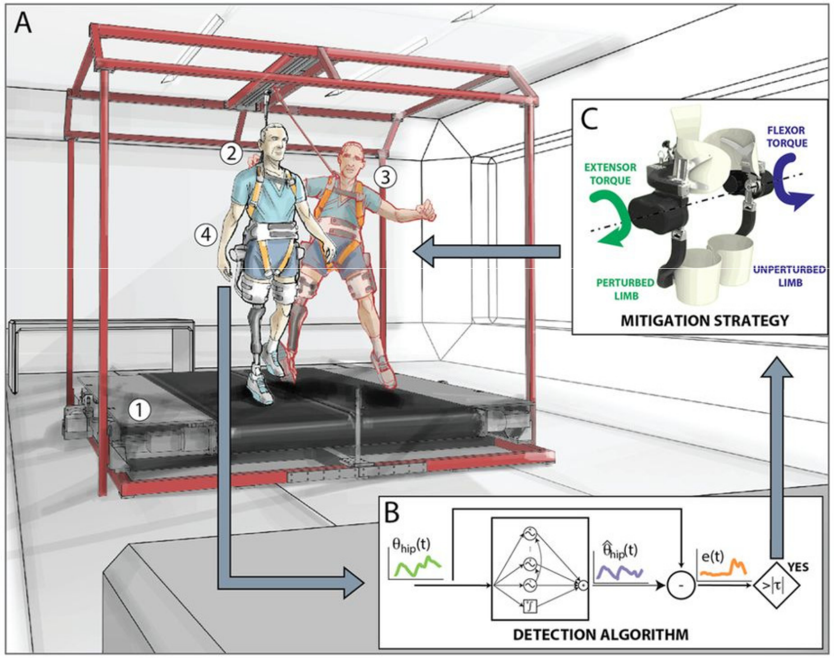


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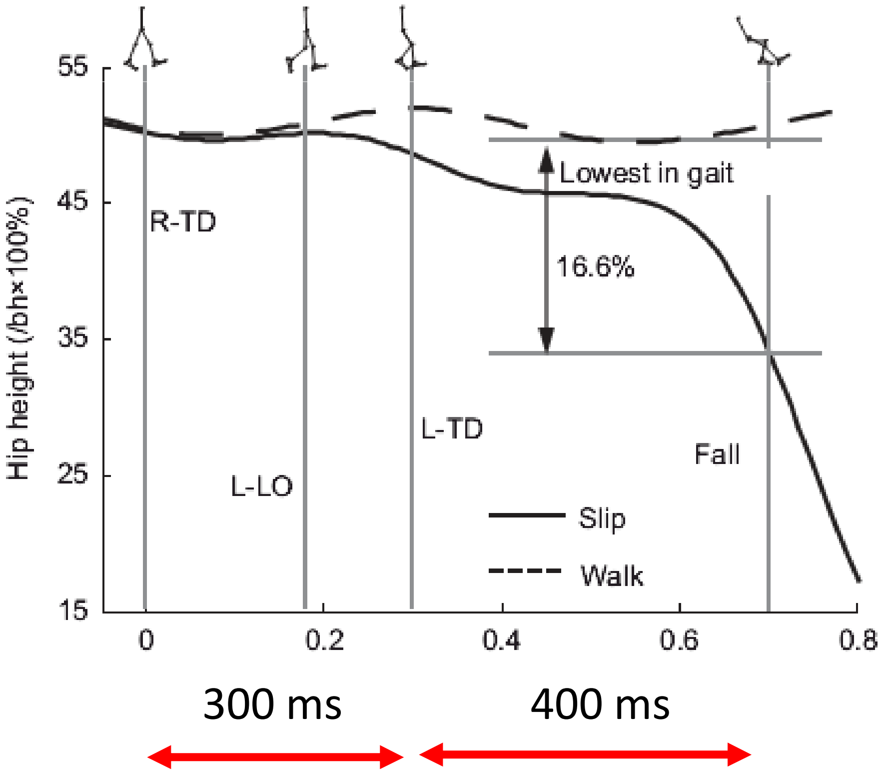
# Detecting the lack of balance

Contents lists available at ScienceDirect
Journal of Biomechanics
journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Role of stability and limb support in recovery against a fall following a novel slip induced in different daily activities

Feng Yang, Tanvi Bhatt, Yi-Chung Pai *

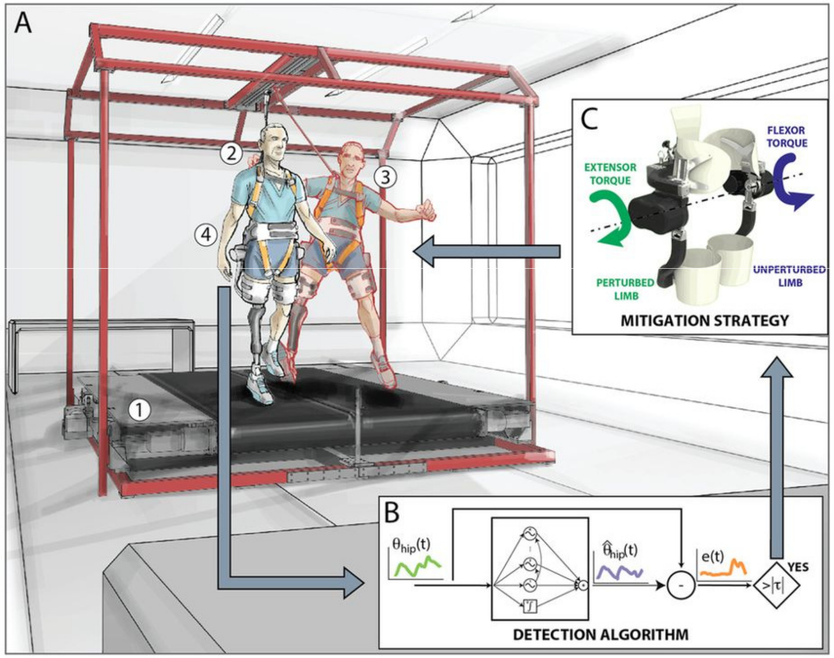



After about 300-400 ms, the lack of balance not longer recoverable and turns to fall

**Q.** Are we on time?

**A.** Yes, just in time (fortunately)

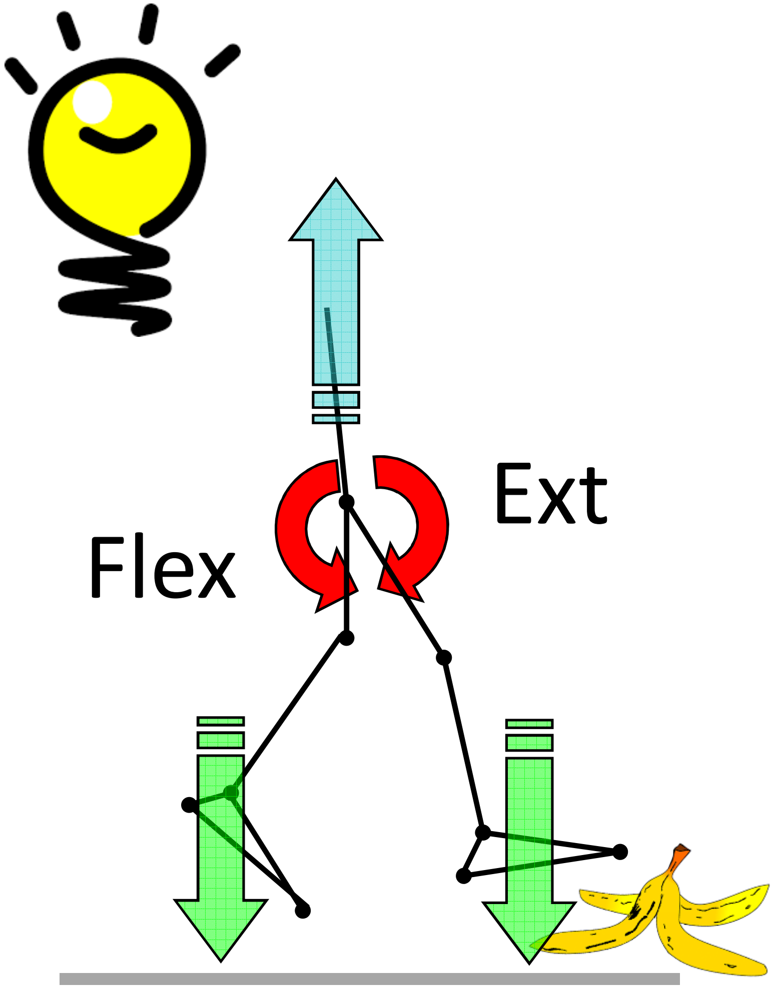
# Overview of the proposed strategy




Main issues:

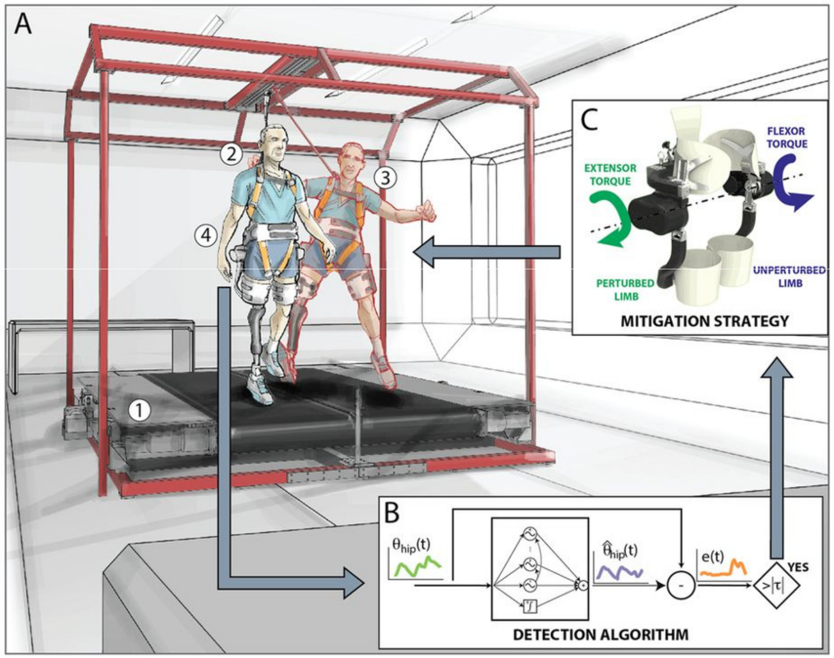
1. Detecting the lack of balance
   - How to do ✓
   - Is it feasible? ✓
   - Is it "on time"? ✓
2. Counteracting the lack of balance
   - How to do
   - Is it effective?
3. Any other approach?

# Counteracting the lack of balance




1. The forward foot starts slipping
2. The algorithm detects the lack of balance [350 ms]
3. The APO acts on the hips
   - Torque 0.2xBW [empirical]
   - To increase the foot-ground interaction
   - To push upward the CoM

# Overview of the proposed strategy

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2. Counteracting the lack of balance
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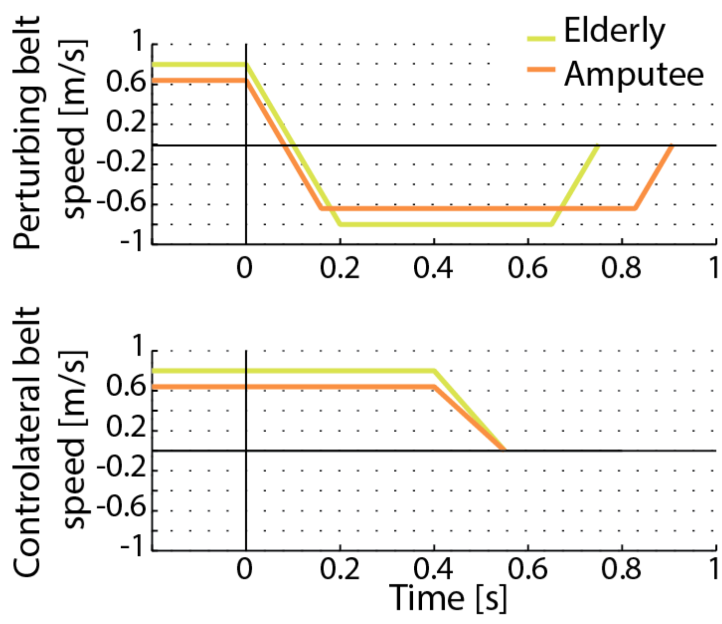
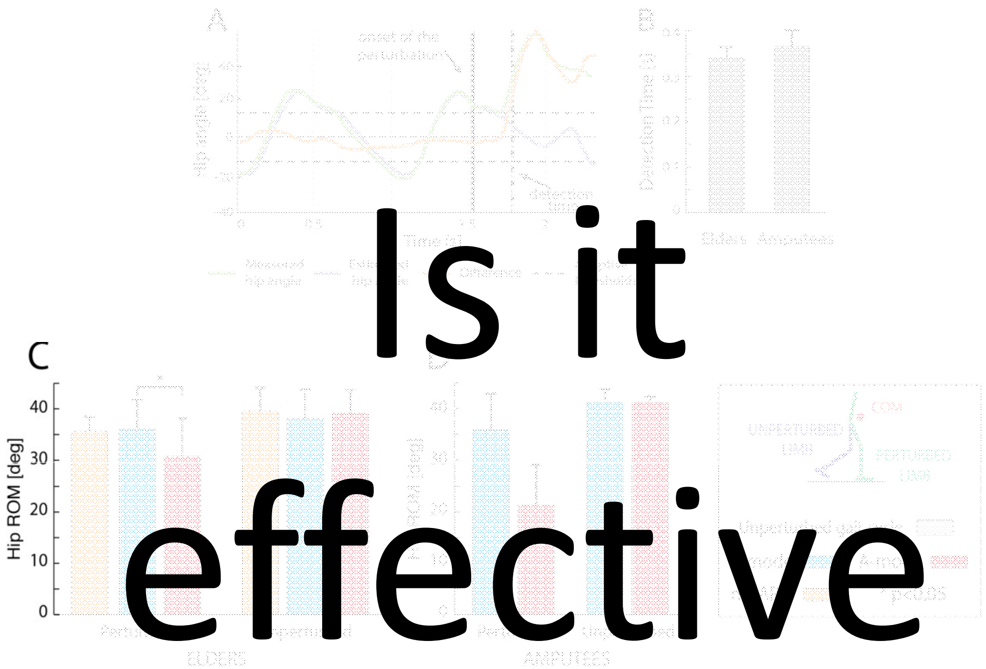
   - Is it effective?
3. Any other approach?

# Materials and Methods

- Participants
  - 8 older adults (males, 69.9±5.1 ys)
  - 2 transfemoral amputees (age- and anthropetry- matched)
  - no other comorbidities
- Walking speed: self selected
  - elders: 0.89±0.11 m/s
  - amputees: 0.69±0.06 m/s
- Perturbation: unexpected slippage
  - elders: right foot
  - amputees: **prosthetic foot**
- Whole body 3D kinematics (34 MRKs)
- APO
  - Z – Mode –> transparent
  - A – Mode -> assistive



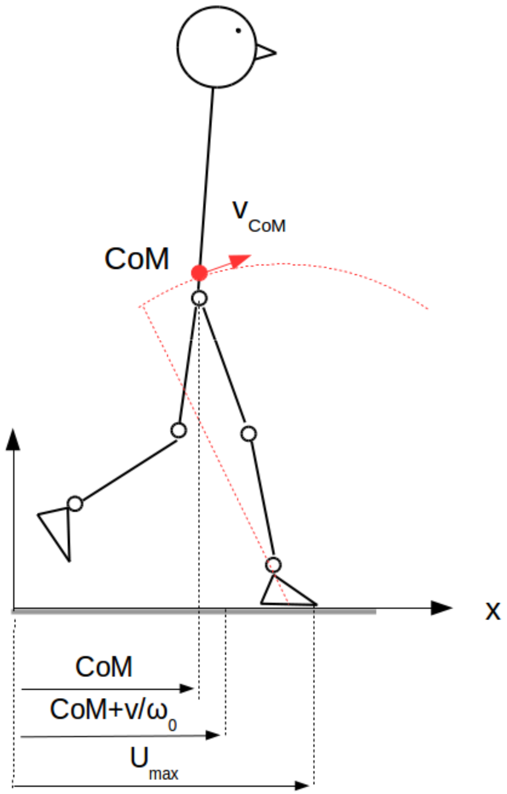
# Counteracting the lack of balance




Is it effective ?

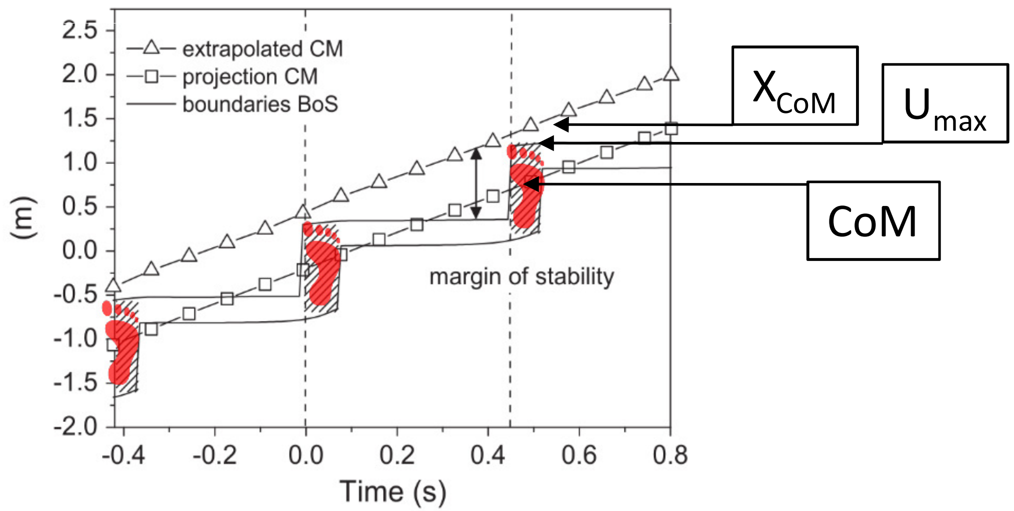
- Detection Algorithm ON TIME
- Faster bipodal support
- Lower num. of recovering steps
- Modification of hip joint angle

# Assessing the Stability: CoM vs BoS
# Margin of Stability




$$MoS = U_{max} - \left( CoM - \frac{v_{CoM}}{\varpi_0} \right) = U_{max} - X_{CoM}$$

$$\varpi_0 = \sqrt{g / h_{CoM}}$$




MoS < 0 [slightly] ---> controllable lack of balance

# Assessing the Stability: CoM vs BoS
# Margin of Stability

$$MoS = U_{\max} - \left( CoM - \frac{v_{CoM}}{\varpi_0} \right) = U_{\max} - X_{CoM}$$

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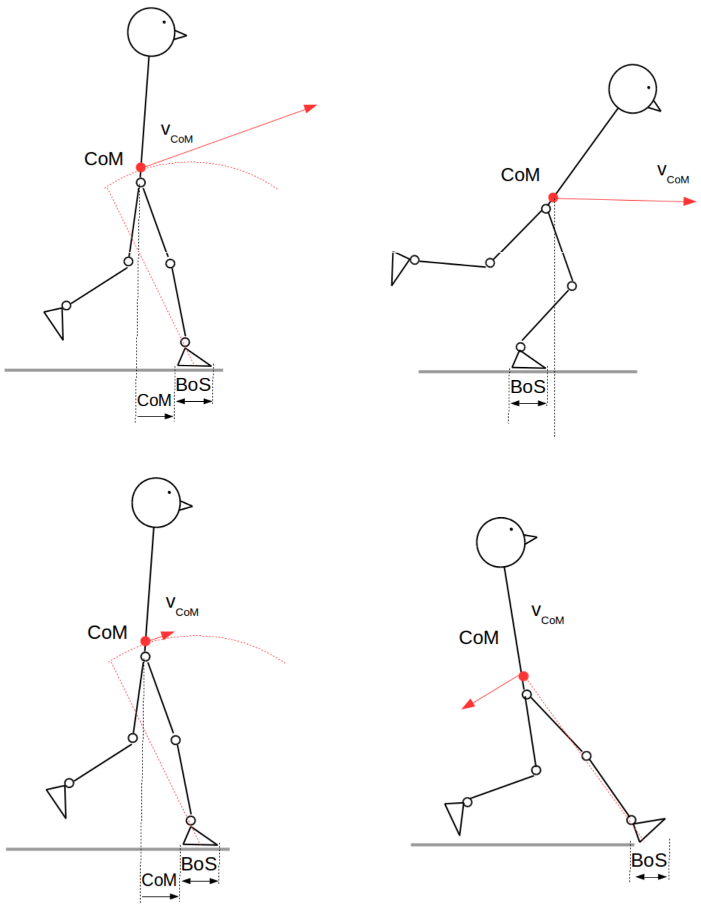
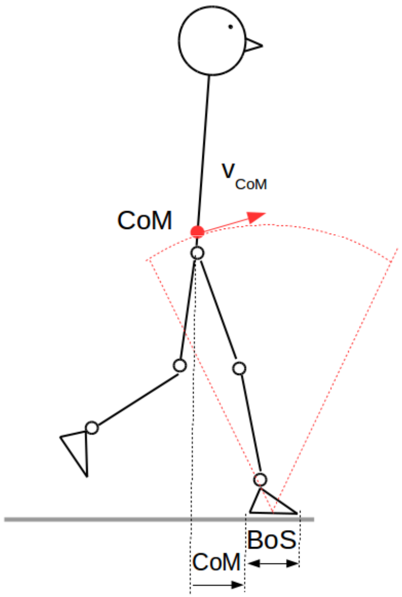
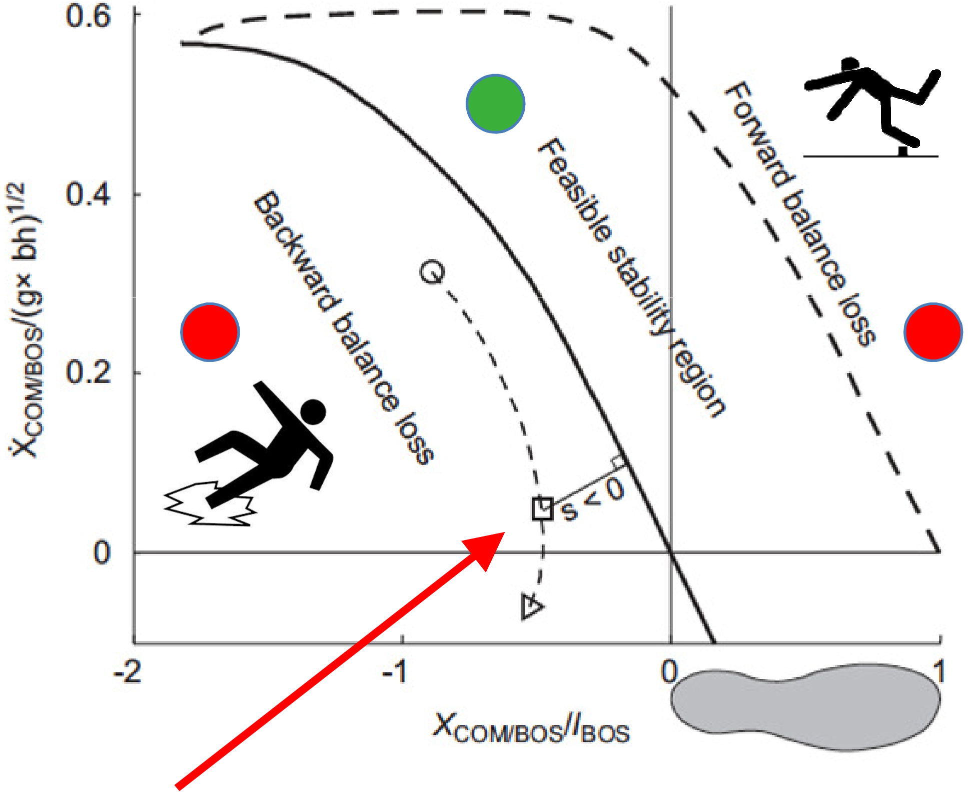



MoS << 0 ---> FORWARD fall

MoS >> 0 ---> BACKWARD fall

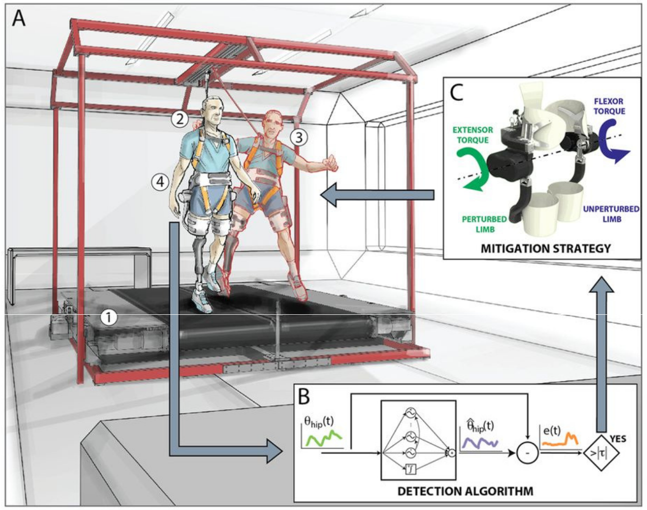
# Assessing the Stability: CoM vs BoS
# CoM Stability

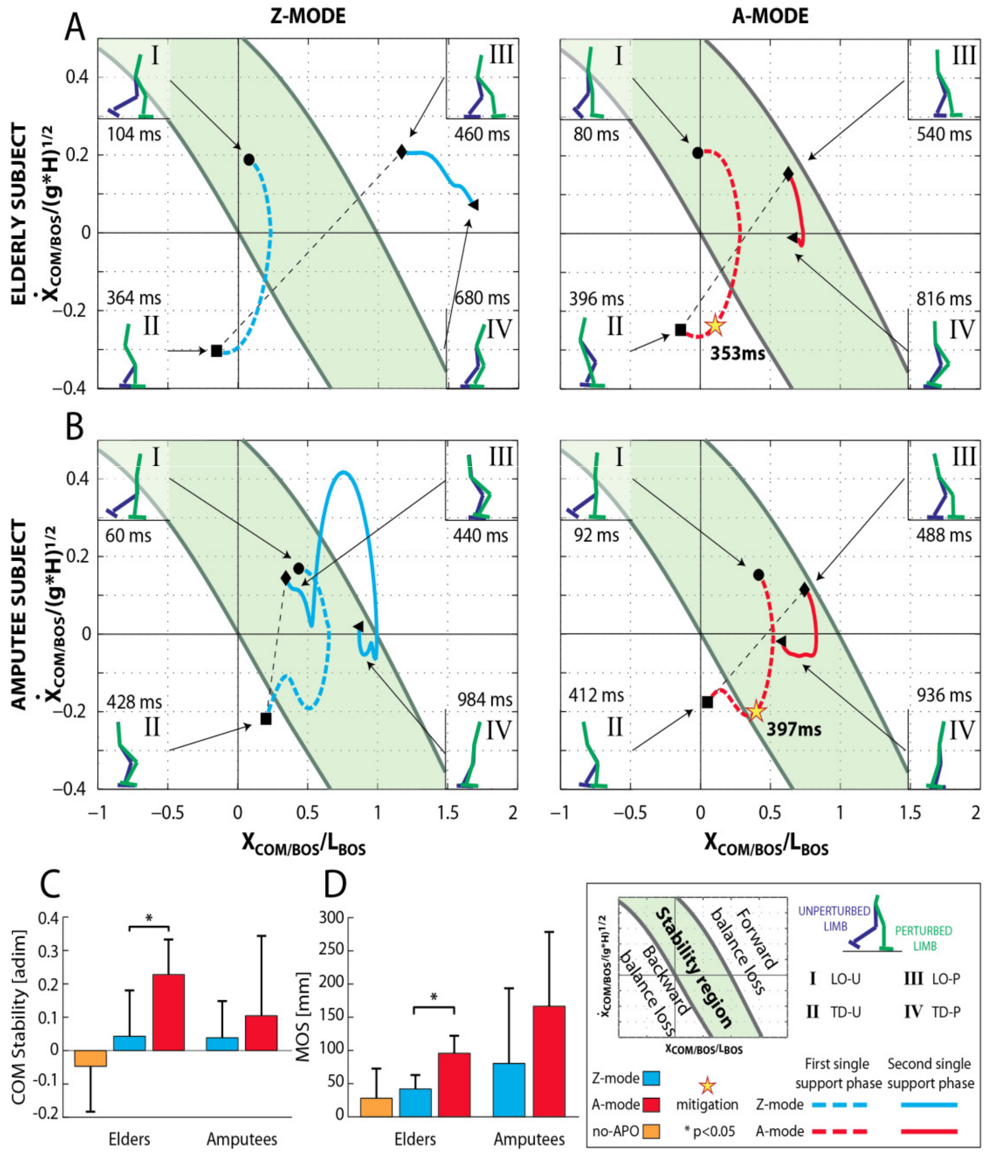



CoM stability

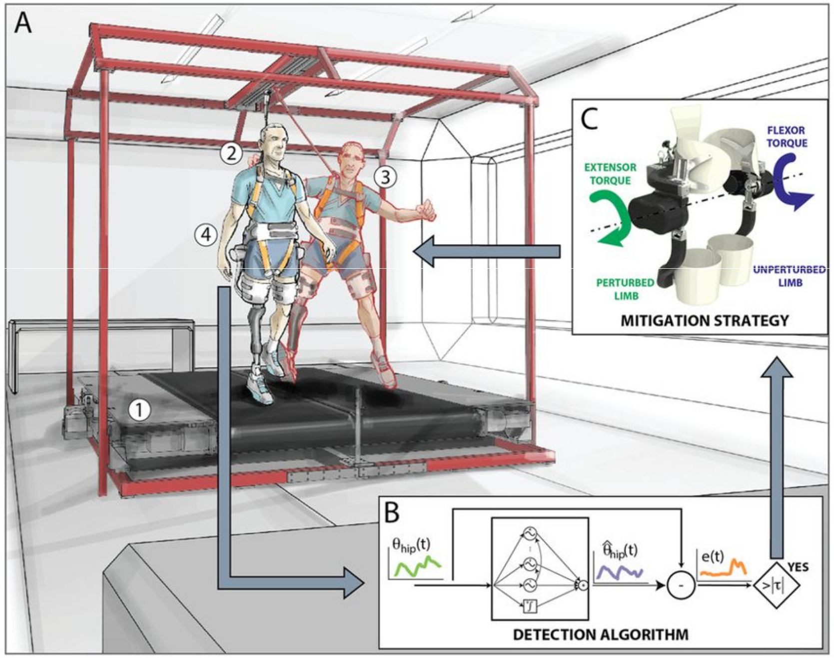
# Counteracting the lack of balance: is it effective?




Yes, it is!

# Overview of the proposed strategy




Main issues:

1. Detecting the lack of balance
   - How to do ✓
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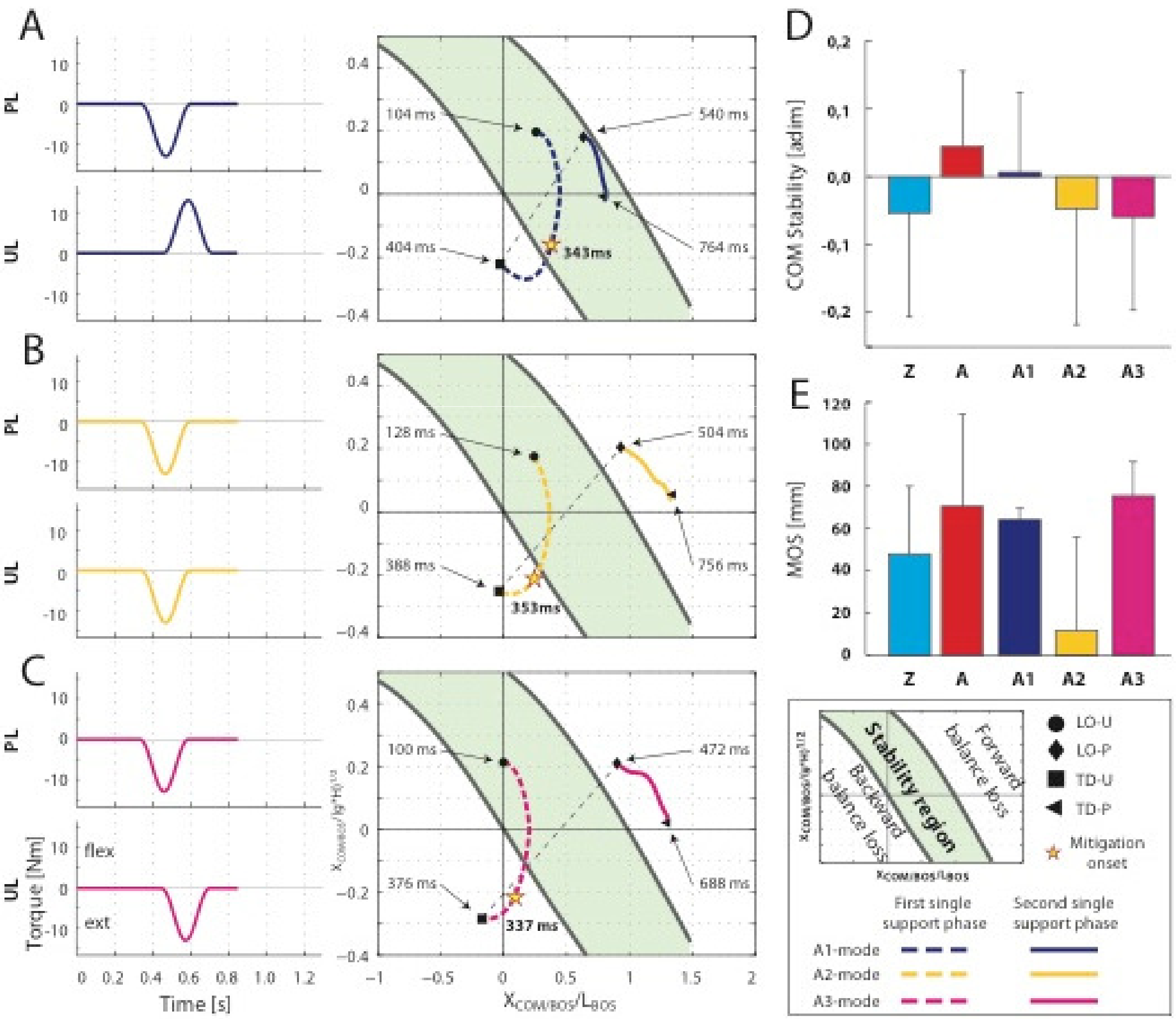
2. Counteracting the lack of balance
   - How to do ✓
   - Is it effective? ✓
3. Any other approach?

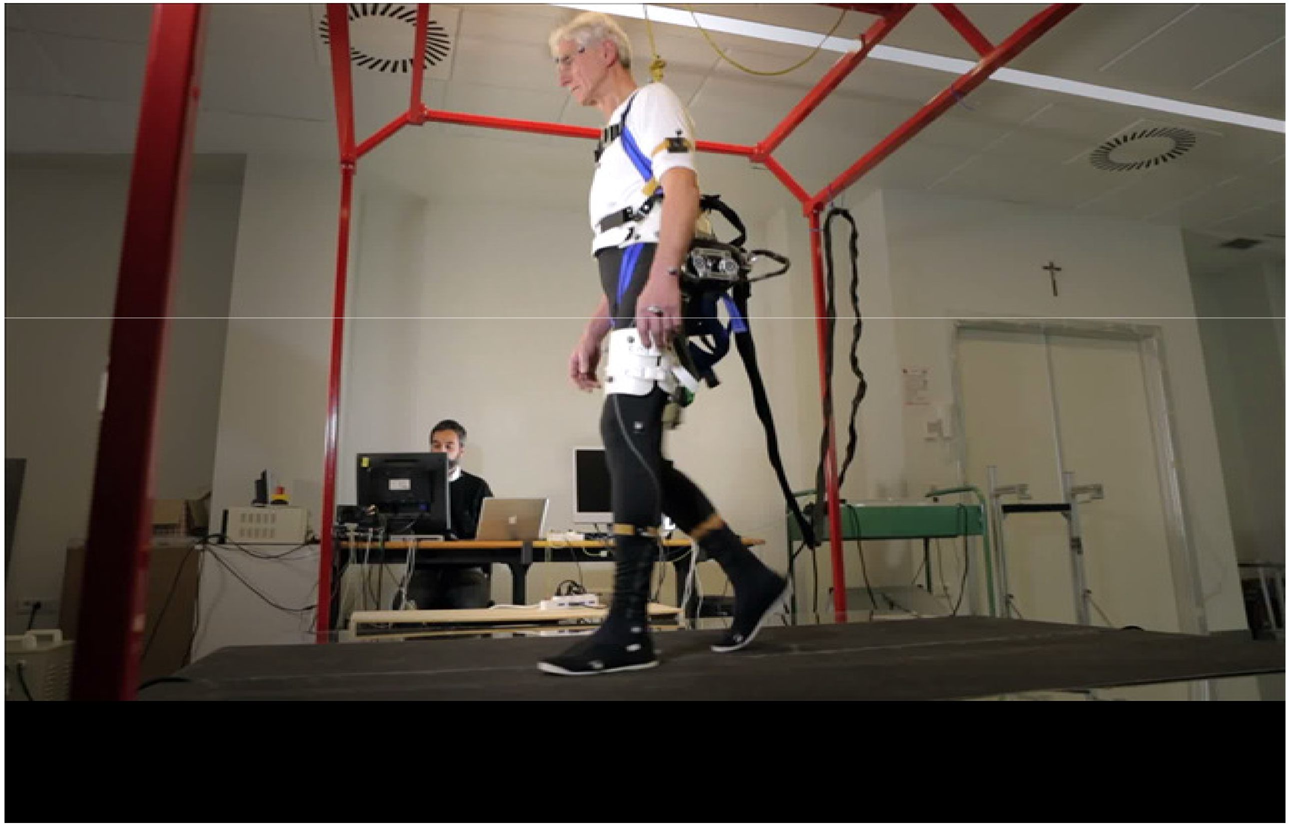
# Counteracting the lack of balance: alternative strategies



# Outline of the presentation

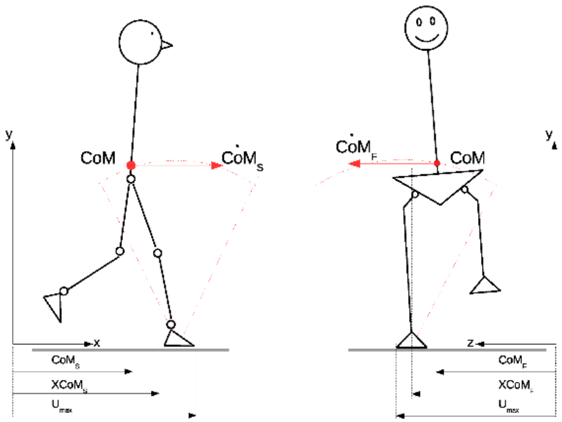
- Fall risk: what are we talking about?
- State of art
  - Assessing the fall risk
  - Detecting falls/lack or balance
  - Counteracting falls/lack of balance
- Wearable robot: the dream
- Our toolbox
  - SENLY
  - Active Pelvis Orthosis
- A possible strategy
  - Detection Algorithm
  - Assistive strategy
- **Ongoing activities**
  - **Different perturbations**
  - **Other approaches for the detection**
  - **Robotic prosthesis**
- Conclusions

# Is the proposed strategy effective after multi-directional slippages?

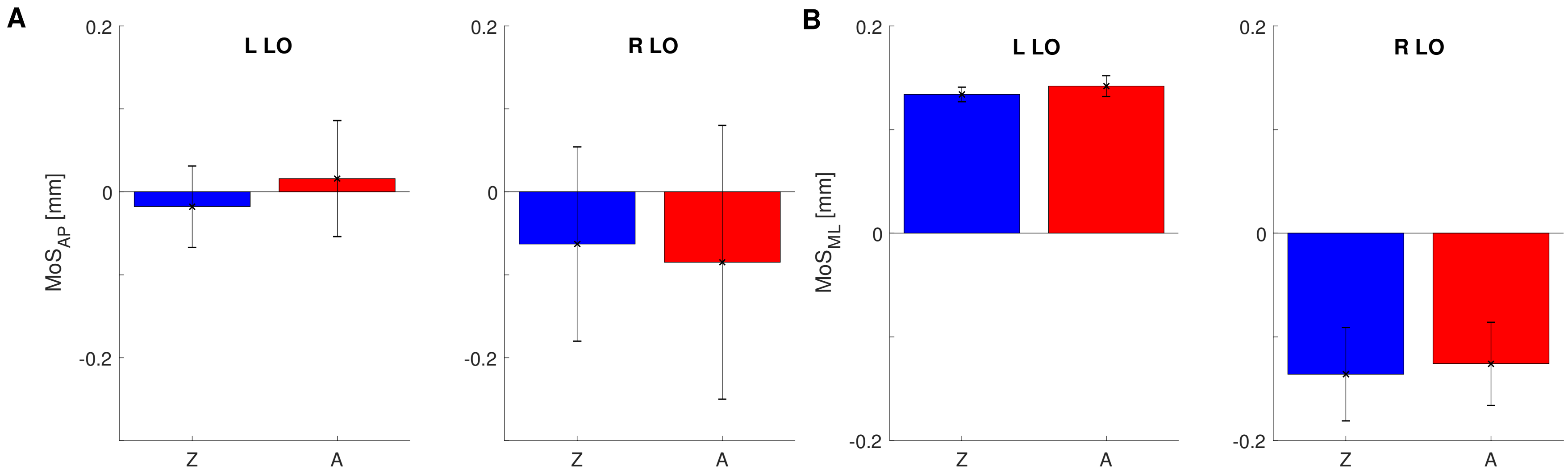


*Aprigliano et al., Robotica 2019*

# Is the proposed strategy effective after multi-directional slippages?




No differences between Z-mode (no assistance) and A-mode (with assistance)

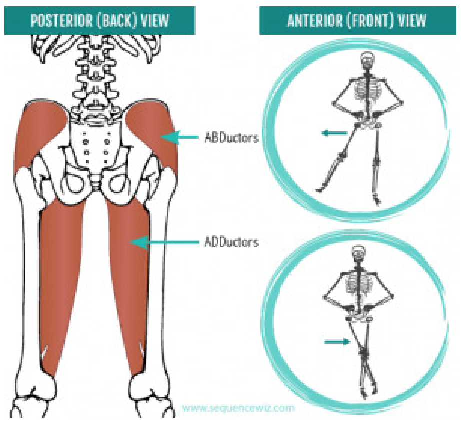


# Is the proposed strategy effective after multi-directional slippages?

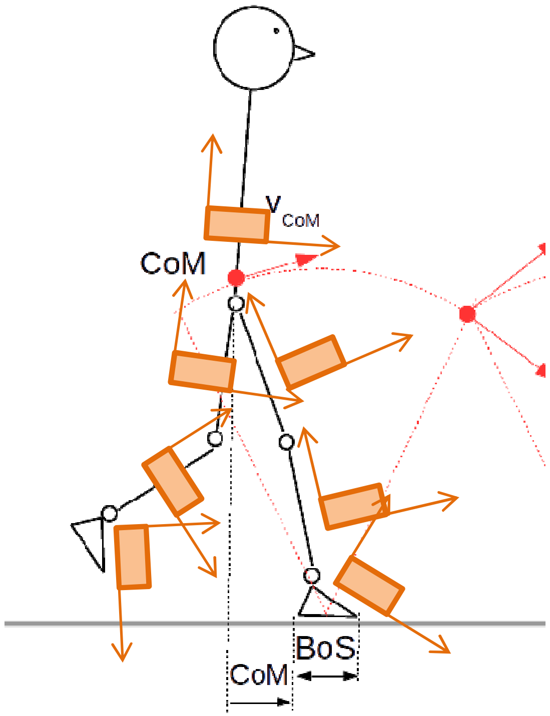
On, it is not effective! Why?

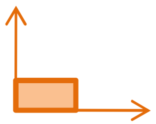
- MDT > 450 ms (too high)
- CLs APO cannot measure and control hip ab/adduction

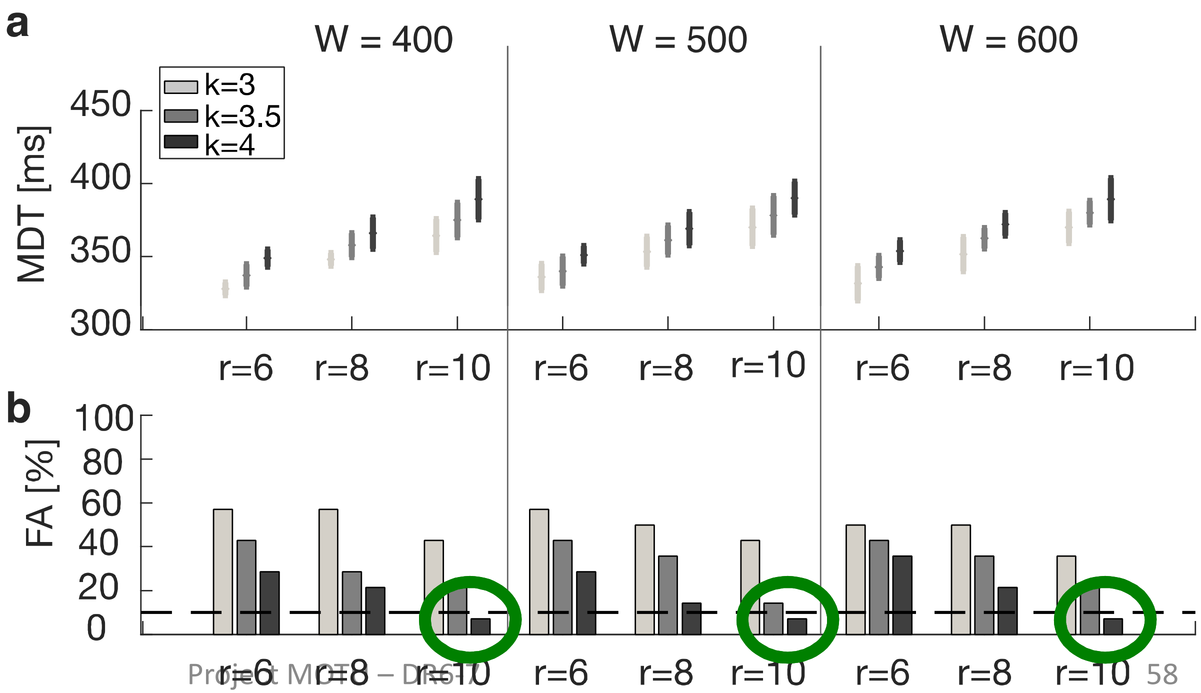
| Tuning parameters | | | | | ML slippages | |
|---|---|---|---|---|---|---|
| $k_P$ | $k_a$ | w | r | k | MDT [ms] | FA [%] |
| 40 | 1 | 900 | 6 | 3.5 | 455±35 | 57 |
| 10 | 1 | 1000 | 10 | 3.5 | 467±21 | 79 |
| 40 | 1 | 1000 | 6 | 3.5 | 461±36 | 50 |



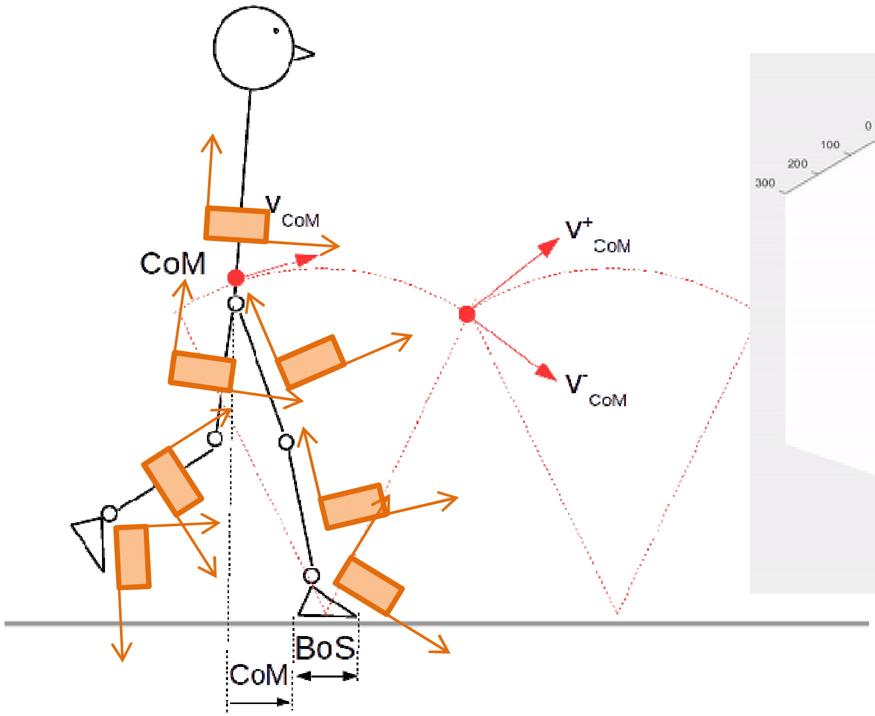
# What about using IMUs?
# Detecting slippages

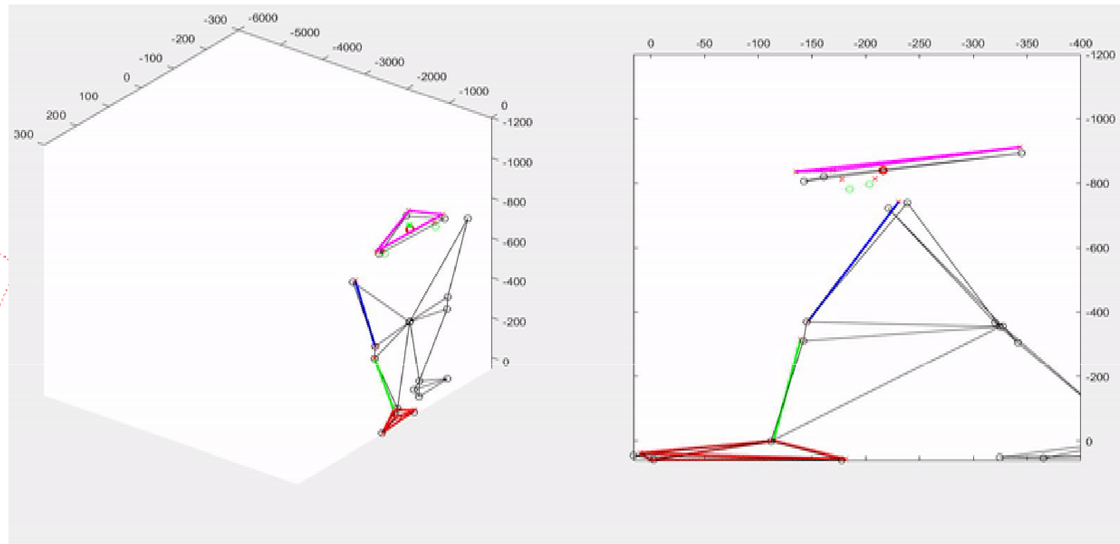


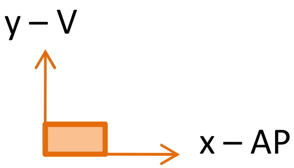



# What about using IMUs?



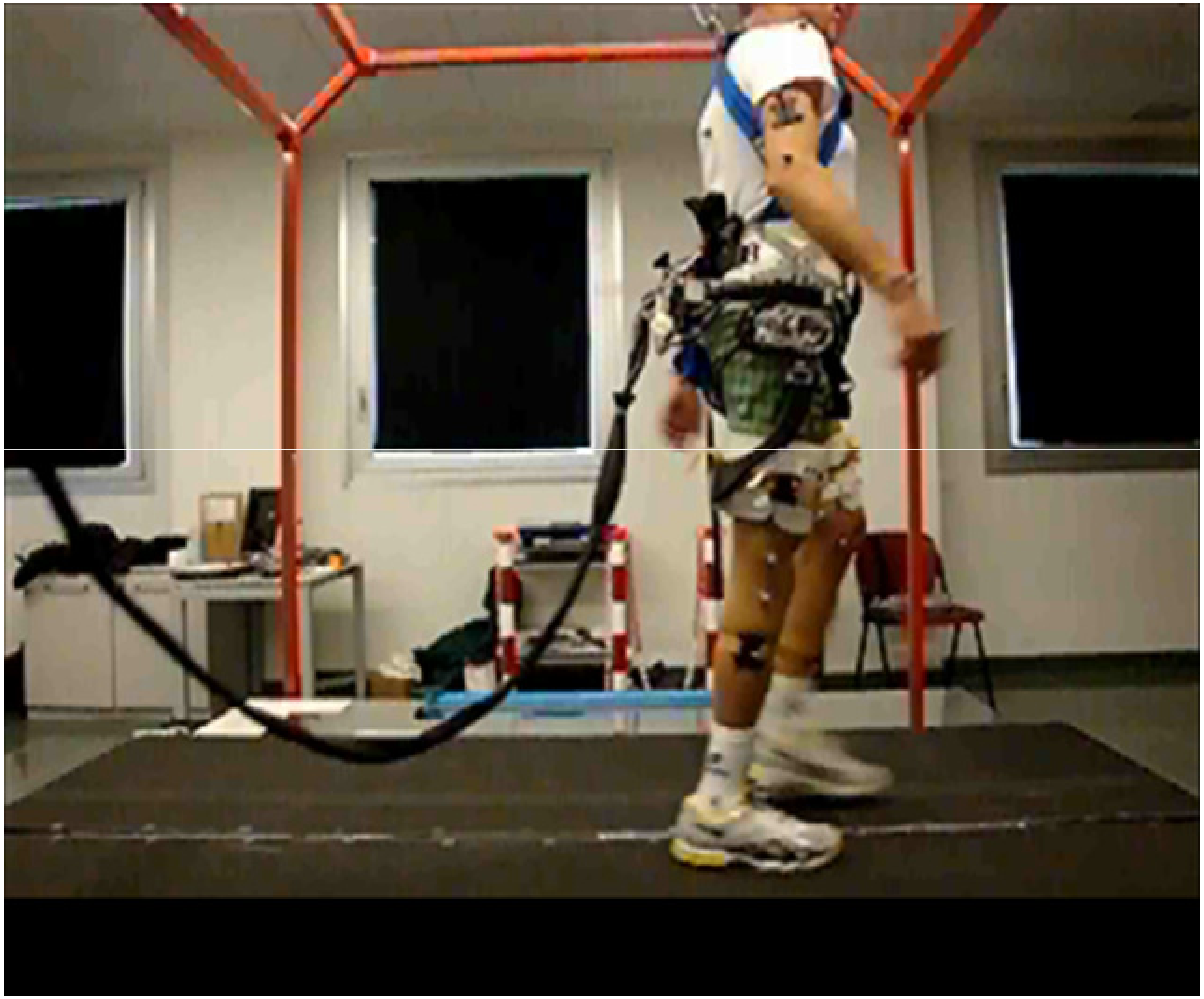





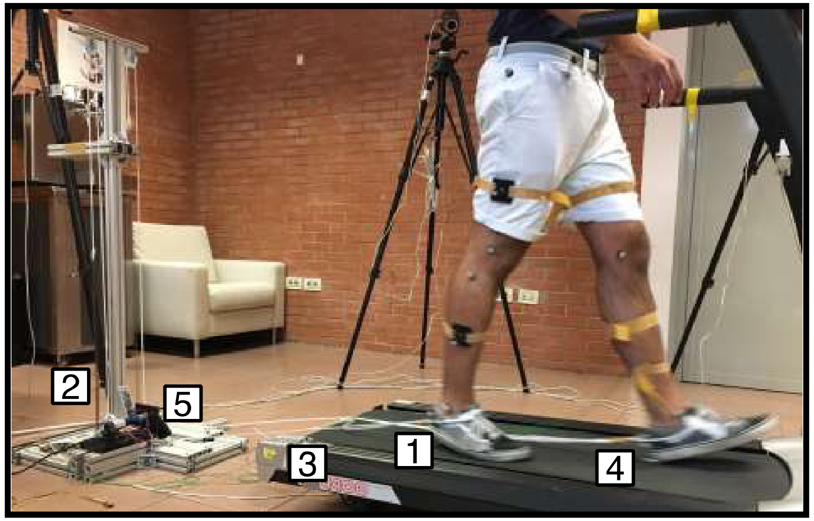

Q. Can we estimate the MOS at run time?

A. Yes, we can!

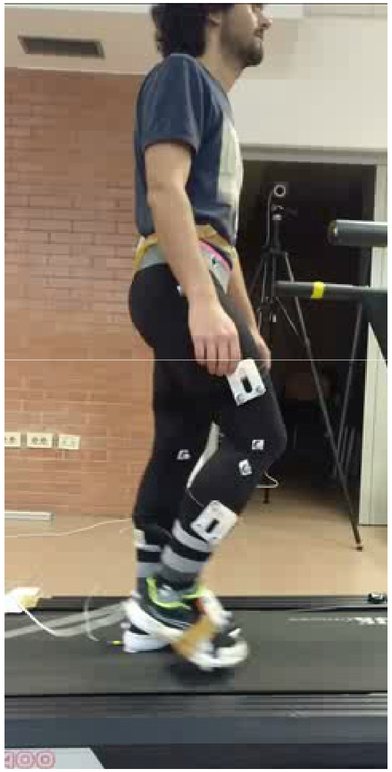
# Robotic prosthesis

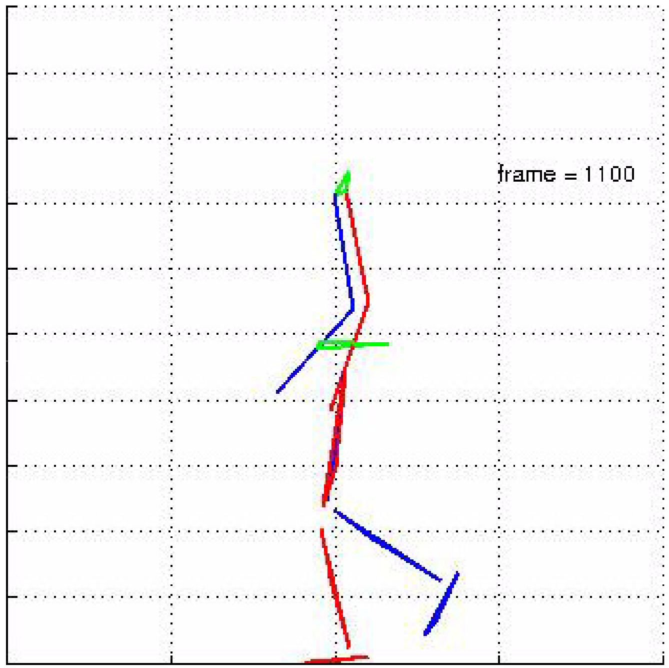


# Tripping

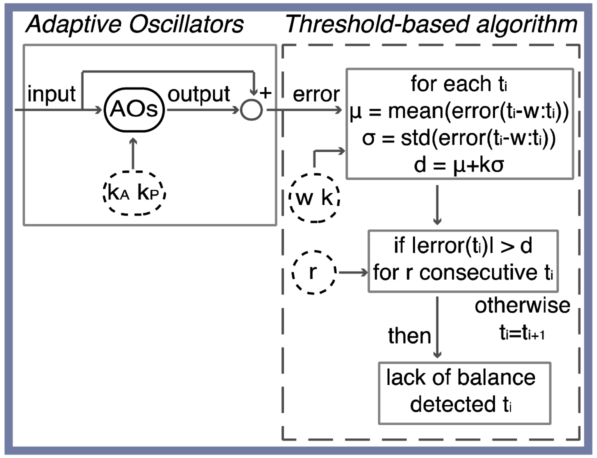


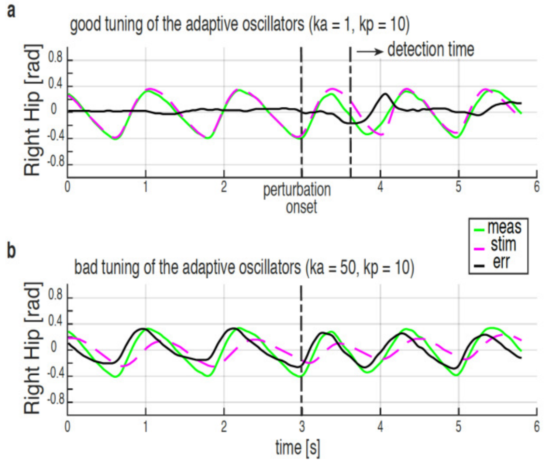

1. perturbed foot; 2. spring-rope mechanisms; 3. treadmill; 4. footswitch under the unperturbed foot; 5. cam-based braking mechanisms.

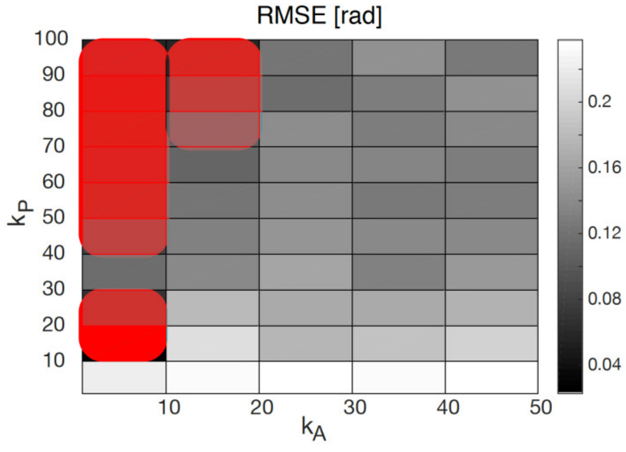


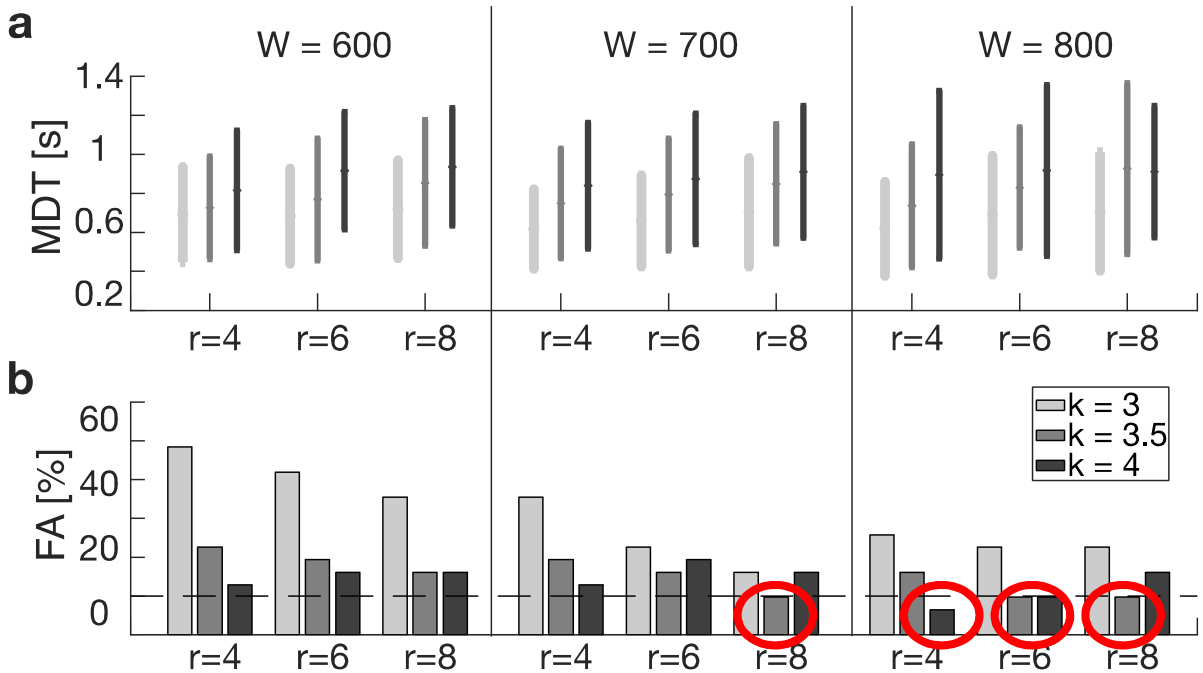


# Tripping: detection based on HIP



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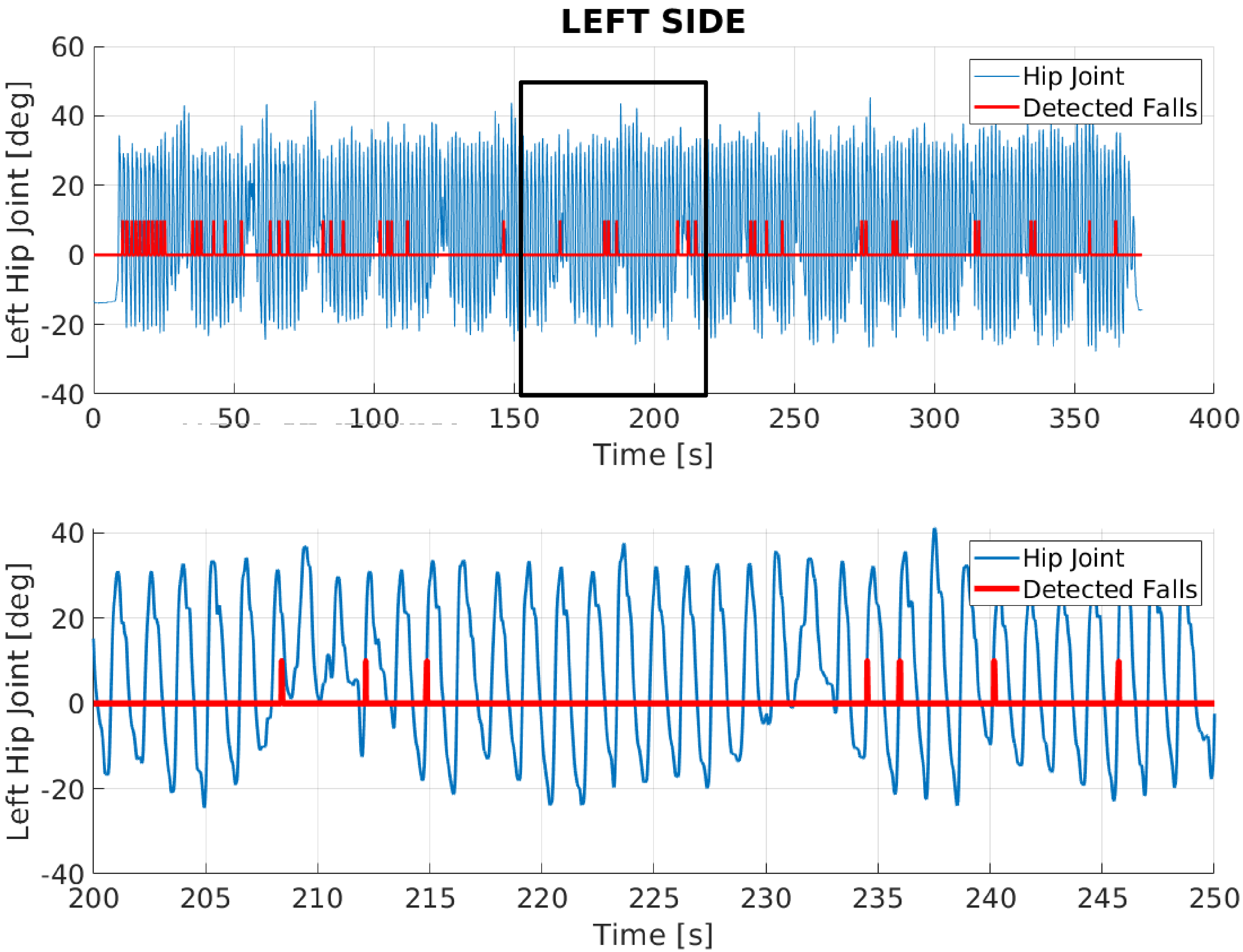
# Conclusions (1/3)



# Conclusions (2/3)

**Q.** Can we generalize the proposed strategy to different perturbations (e.g., tripping, obstacle avoidance)?

**A1.** The “detection” procedure can be easily generalized even if tests in ecological conditions are required.

**A2.** The APO-mediated assistive behavior needs to be investigated

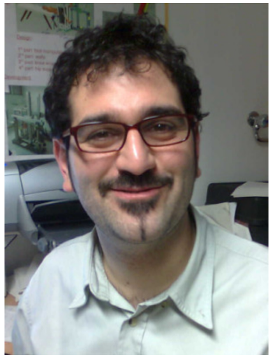
# Conclusions (3/3)

**Q.** Any limit?

**A.** A bunch of limits!!!
However, we hope to be on the right way.

# Acknowledgments (1/2)

S. Micera



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HORIZON 2020

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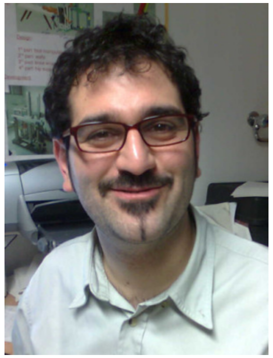

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MOTU
A novel paradigm of robotic transfemoral prosthetic systems

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INAIL
Centro Protesi

Fondazione Don Carlo Gnocchi Onlus

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- Aprigliano et al., *"Effectiveness ofaRobot-Mediated Strategy While Counteracting Multidirectional Slippages"*, Robotica 2019 (in press)


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# Counteracting balance loss by using wearable robotics

Speaker: Vito Monaco

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POLITECNICO DI BARI

*Bari, 20 May 2019*