

# Digitale tweelingen

Predictieve simulaties van wandelen voor de klinische gangbeeldanalyse

Tom Buurke, Friedl De Groot, Tim van der Zee, Ellis Van Can, Ines Vandekerckhove  
Workshop SMALLL Congres 2025, Erasmus MC, Rotterdam, NL

umcg:

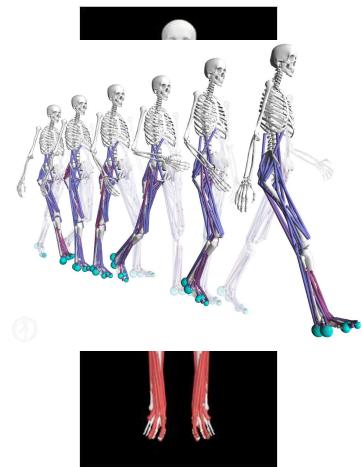
SMALLL  
Society for Movement Analysis Laboratories in the Low Land

KU LEUVEN

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## Predictieve simulaties van wandelen voor de klinische gangbeeldanalyse

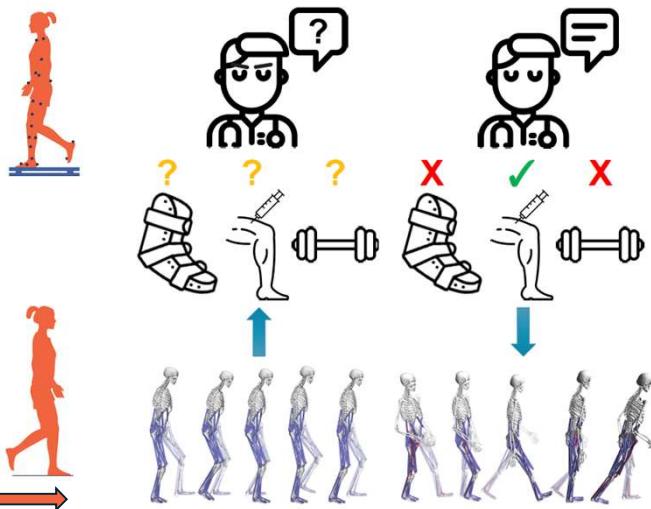
- Wat is een musculoskeletaal model?
  - Wiskundig model
  - Starre lichamen (botten)
  - Verbonden met gewrichten
  - Spieren over de gewrichten
  - Spieren genereren kracht en beweging



# Waarom gebruiken we musculoskeletaal modellen?

## **Vanuit gemeten data**

- Modelleren wat we niet kunnen meten
    - Spierkracht
    - Interne belasting
    - Spier-pees lengte



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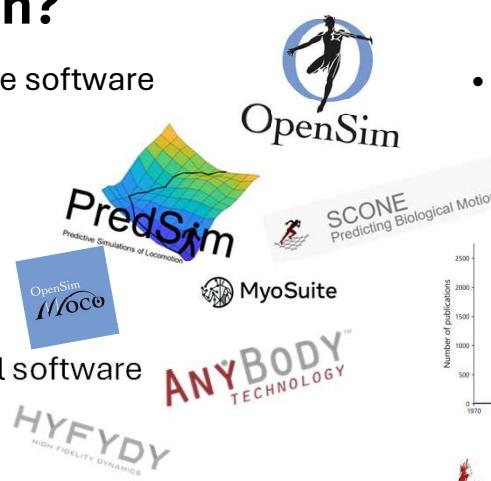
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Illustrations from Uchida & Delp (2020)

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# Hoe gebruiken we musculoskeletale modellen?

- Open-source software
    - OpenSim
    - PredSim
    - SCONE
    - Moco
    - MyoSuite
    - ...



- Simulation CPU time
    - 2001: 10,000 hours<sup>1</sup>
    - 2019: 1 hour<sup>2</sup>

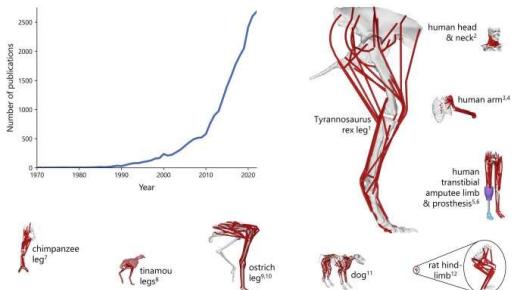
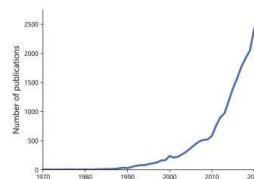


Figure from Uhrlrich et al. (2023)

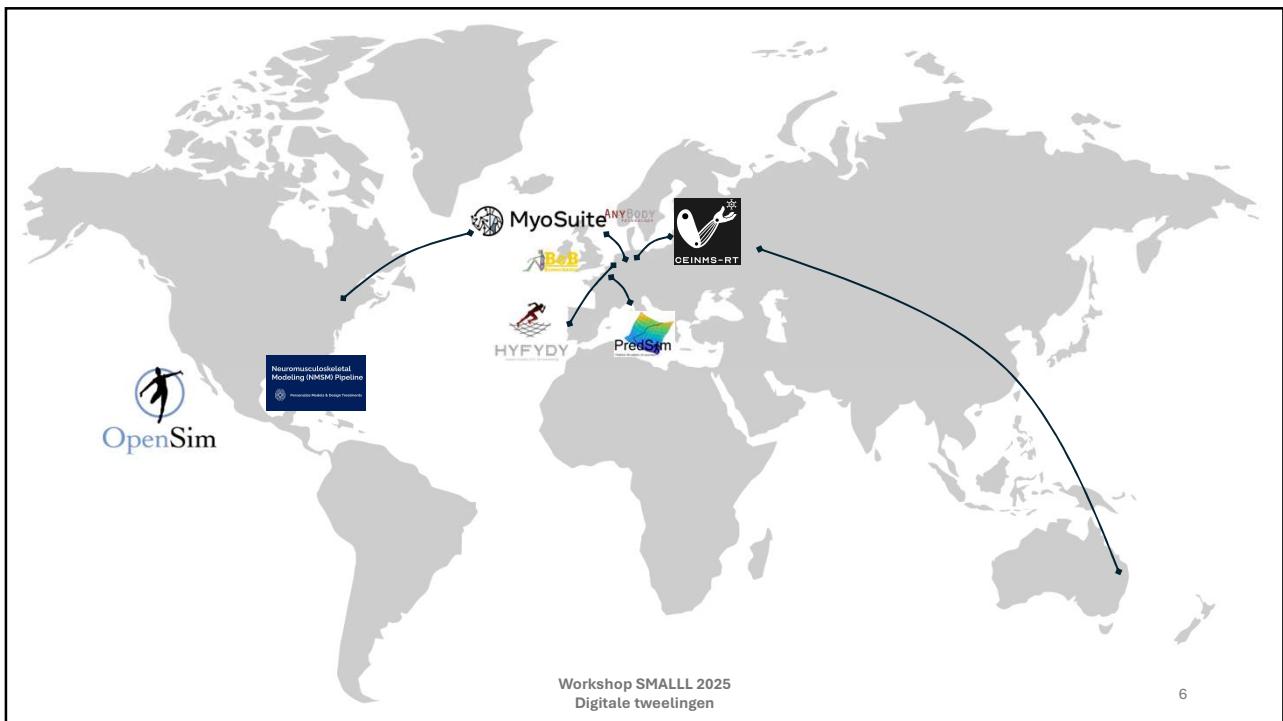
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1) Anderson & Pandey (2001)

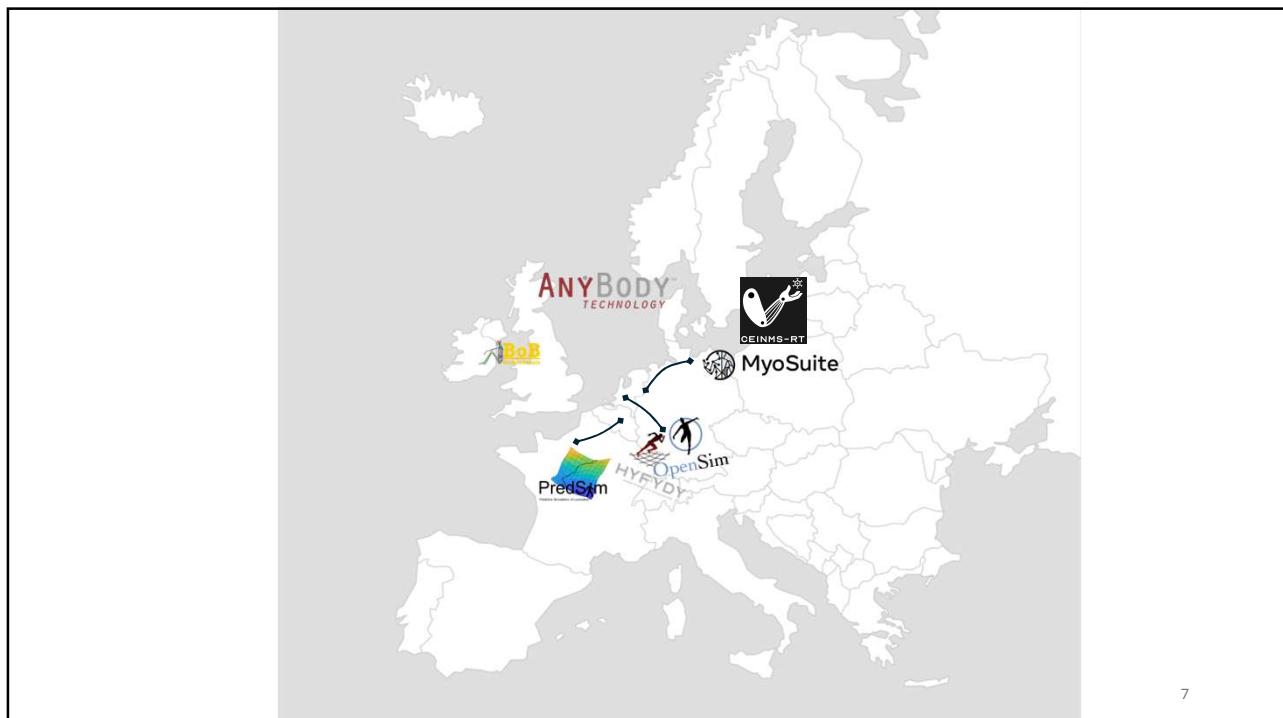
- 1) Anderson & Pandy (2005)
- 2) Falisse et al. (2019)



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## Het doel van vandaag

Na deze workshop...

- kent u de onderliggende theorie van musculoskeletaal modelleren en predictieve simulaties.
- kunt u predictieve simulaties met 2D modellen in *PredSim* uitvoeren.
- kunt u de informatie en bronnen voor 3D simulaties vinden.
- kent u kansen en obstakels voor de klinische implementatie van predictieve simulaties.



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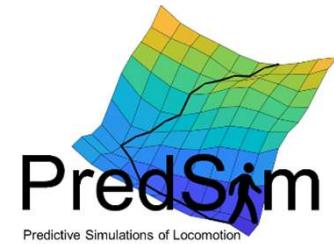
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# Programma

00:00 – 00:15: Introductie en theorie

- Predictieve simulaties voor de klinische gangbeeldanalyse (Tom Buurke)
- Onderliggende theorie van modelleren en simulaties met **PredSim** (Friedl De Groot)



00:15 – 00:30: De casussen van vandaag: Wat kunnen we personaliseren en simuleren?

- Casus 1: Spierzwakte en -stijfheid bij Duchenne spierdystrofie (Ines Vandekerckhove)
- Casus 2: Chirurgische ingreep bij cerebrale parese (Ellis Van Can)
- Casus 3: Het effect van een enkel-voet-orthese bij een dropvoet (Tim van der Zee)

00:30 – 01:00: Hands-on: Predictieve simulaties in 2D met PredSim

01:00 – 01:15: Afsluitende discussie

- Showcase: Predictieve simulaties in 3D (Friedl De Groot)
- Groepsdiscussie: Kansen en obstakels voor de klinische implementatie van predictieve simulaties (Tom Buurke)

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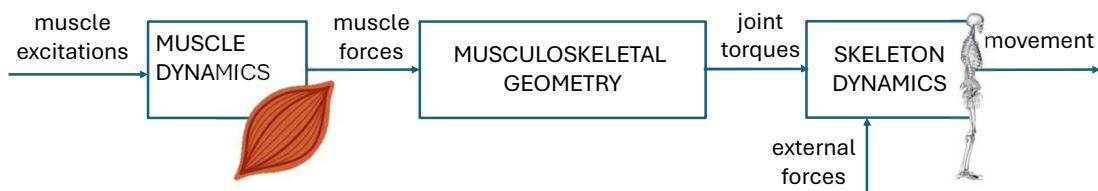
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## Simulations based on a musculoskeletal model



Monty Python: Ministry of silly walks

dynamic constraints



task constraints, e.g. average forward speed and periodicity for locomotion

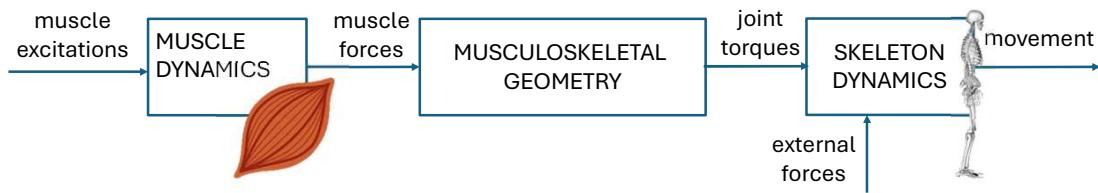
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## Optimal control assumption

**find** muscle excitations **that**  
**minimize** cost  
**subject to**  
dynamic constraints

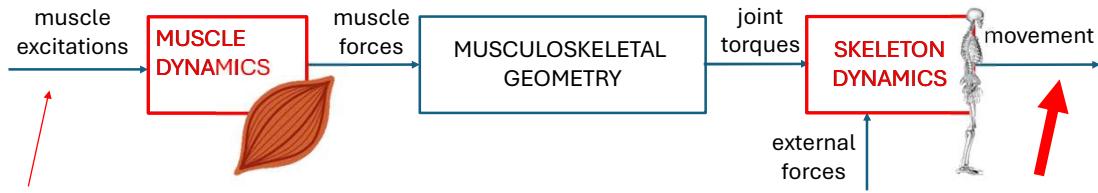


task constraints, e.g. average forward speed and periodicity for locomotion

## Solving optimal control problems

**find** muscle excitations **that**  
**minimize** cost  
**subject to**  
dynamic constraints

STIFF DIFFERENTIAL EQUATIONS



task constraints, e.g. average forward speed and periodicity for locomotion

## We reduced computational cost by factor 20

Challenge: High computational cost of numerical methods

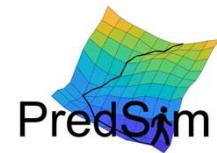
Muscle-driven 3D model (23 dofs, 54 muscles)  
~**10,000 hours** (Anderson and Pandy, 2001)

Muscle-driven 3D model (23 dofs, 40 muscles)  
~**60 hours** (Miller, 2014)

Muscle-driven 3D model (25 dofs, 80 muscles)  
~**13-17 hours** (Lin ... Pandy, 2018)

Muscle-driven 3D model (29 dofs, 92 muscles)  
**< 1 hour** (Falisse ... De Groot, 2019)

2001  
2014  
2018  
2019



Predictive simulations of muscle driven 3D walking allow us to explore effect of neuro-musculoskeletal deficits

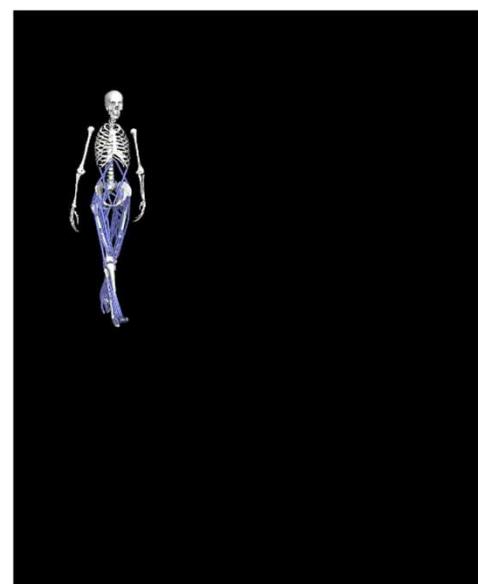


minimize cost



subject to

- muscle dynamics
- skeleton dynamics
- symmetry or periodicity
- desired walking speed



## Model predicts a continuum of walking and running gaits

0.73 ms<sup>-1</sup>      CPU time  
1.23 ms<sup>-1</sup>      35 ± 14 min  
1.73 ms<sup>-1</sup>  
2.23 ms<sup>-1</sup>  
2.73 ms<sup>-1</sup>

FASTER →

Playback speed is 0.2 x real time

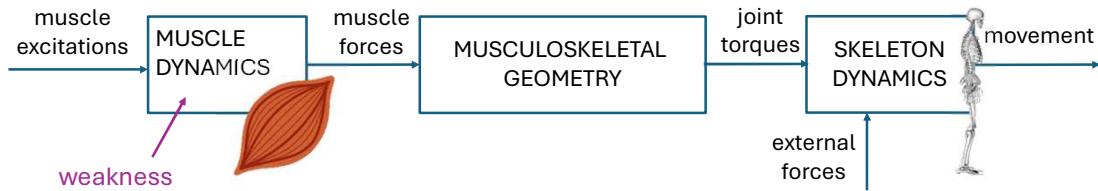


Predictive simulations of walking and running

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## Modeling impairments

**minimize cost**  
**with respect to muscle excitations**  
**subject to**  
**dynamic constraints**



task constraints, e.g. average forward speed and periodicity for walking

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## Decreased hip actuator strength led to compensated Trendelenburg (hip circumduction and trunk sway)

Unimpaired

Weakened by 50%

Weakened by 75%

Weakened by 90%

Increasing weakness →

Playback speed is 0.2 x real-time



Effect of weakening the hip muscles on predicted walking patterns

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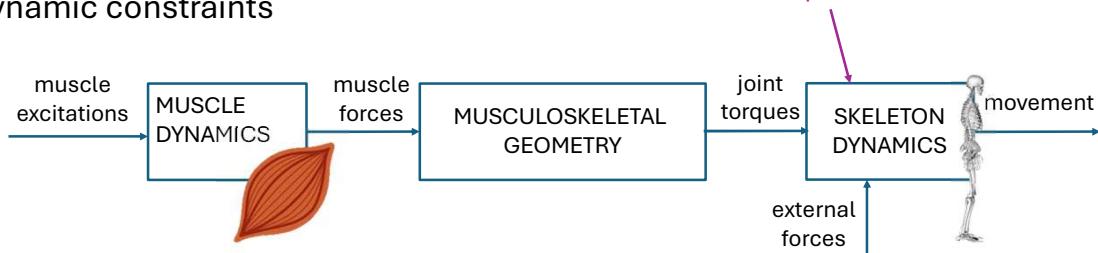
## Modeling impairments

**find** muscle excitations **that**

**minimize** cost

**subject to**

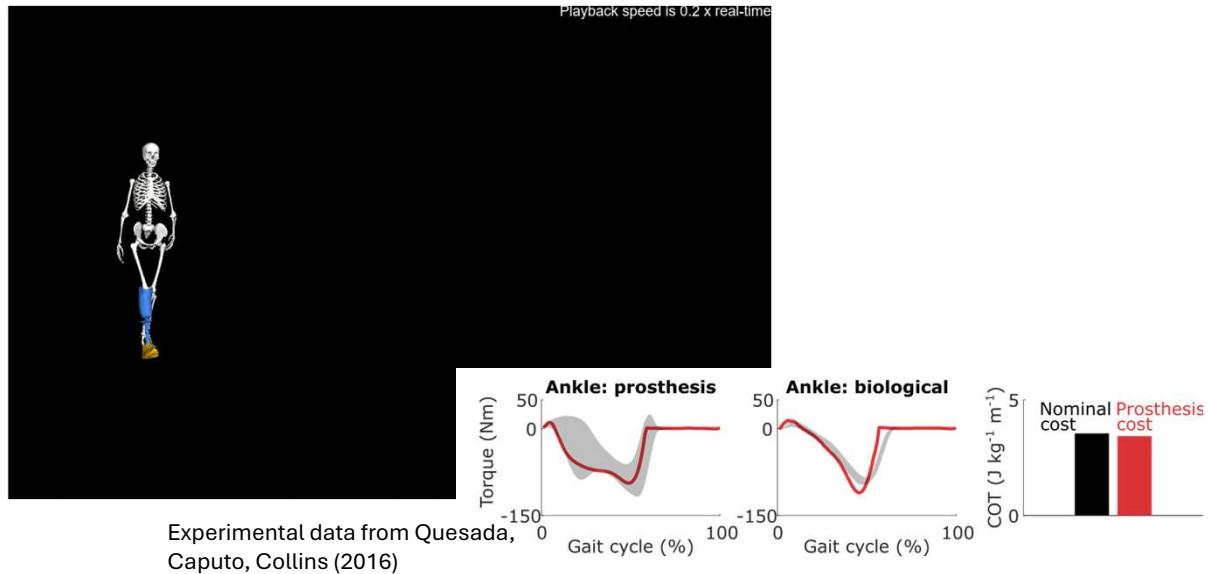
dynamic constraints



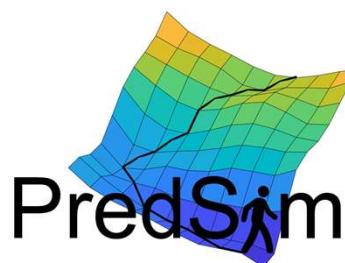
task constraints, e.g. average forward speed and periodicity for walking

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Prosthetic use altered the ankle torque  
in agreement with experimental data



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Muscle dynamics

Definition of optimal control problem



MATLAB

Skeleton dynamics using modified version of OpenSim that enables algorithmic differentiation



OpenSim

Musculoskeletal geometry

CasADI for algorithmic differentiation and formulating optimization problem (solved using ipopt)



<https://web.casadi.org/>

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## Why use PredSim software?

PredSim versus OpenSim Moco

	PredSim	OpenSim Moco (Dembia, Bianco et al. <i>PLOS COMP. BIOL.</i> 2020)
Simulation type	Predictive	Predictive, tracking or inverse
Task	Steady-state locomotion	Any task
Discretisation	Direct collocation	Direct collocation
Formulation of dynamics	Implicit	Implicit or explicit
Derivatives	Algorithmic differentiation	Finite differences

AD is faster than FD, and more so for more complex models  
(Falisse, Serrancolí et al. *PLOS ONE* 2019)

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## Customise and run simulations from a single script

```
% Path to OpenSim model file
osim_path = './Subjects/Falisse_et_al_2022/Falisse_et_al_2022.osim';

% Initialize settings to what was used for this model in the paper
[S] = initializeSettings('Falisse_et_al_2022');

% Path to folder to save the simulation result
S.misc.save_folder = '../PredSimResults/Falisse_et_al_2022';

% Select cold-start initial guess
S.solver.IG_selection = 'quasi-random';

% Run simulation
runPredSim(S, osim_path);
```

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## OpenSim model file

```
% Path to OpenSim model file  
osim_path = './Subjects/Falisse_et_al_2022/Falisse_et_al_2022.osim';
```

Example models:

- |                          |                    |
|--------------------------|--------------------|
| • Falisse_et_al_2022     | 31 DoFs 92 muscles |
| • DHondt_et_al_2024_3seg | 31 DoFs 92 muscles |
| • DHondt_et_al_2024_4seg | 33 DoFs 94 muscles |
| • Gait1018               | 10 DoFs 18 muscles |



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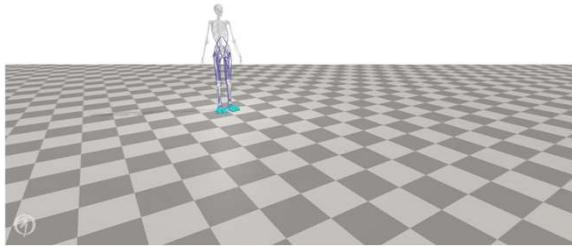
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## A few required settings ...

```
% Path to OpenSim model file  
osim_path = './Subjects/Falisse_et_al_2022/Falisse_et_al_2022.osim';  
  
% Initialize settings to what was used for this model in the paper  
[S] = initializeSettings('Falisse_et_al_2022');  
  
% Path to folder to save the simulation result  
S.misc.save_folder = '../PredSimResults/Falisse_et_al_2022';  
  
% Select cold-start initial guess  
S.solver.IG_selection = 'quasi-random';
```

} important settings: no defaults



Alternative initial guess: OpenSim motion file

- Experimental data
- Previous result
- Custom

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## ... and many optional settings

- subject
- orthosis
- metabolicEnergy
- weights
- solver
- bounds
- OpenSimADOptions
- post\_processing
- misc (task constraints, file paths, scaling, ...)

This workshop

```
% Average forward speed of pelvis  
S.misc.forward_velocity = 0.8;  
  
% Periodic and symmetric  
S.misc.gaitmotion_type = 'HalfGaitCycle';  
initial kinematics, activations  
= mirrored final kinematics, activations  
(except forward position)  
  
% Periodic  
S.misc.gaitmotion_type = 'FullGaitCycle';  
initial kinematics, activations  
= final kinematics, activations  
(except forward position)
```

"initial" can be any point in the cycle  
e.g. 80 – 20% is also half cycle

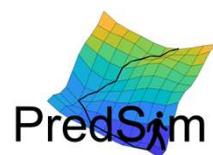
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## De casussen van vandaag: Wat kunnen we personaliseren en simuleren?

- Casus 1: Spierzwakte en -stijfheid bij Duchenne spierdystrofie  
(Ines Vandekerckhove)
- Casus 2: Chirurgische ingreep bij cerebrale parese  
(Ellis Van Can)
- Casus 3: Het effect van een enkel-voet-orthese bij een dropfoot  
(Tim van der Zee)

Op basis van 2D musculoskeletale modellen.



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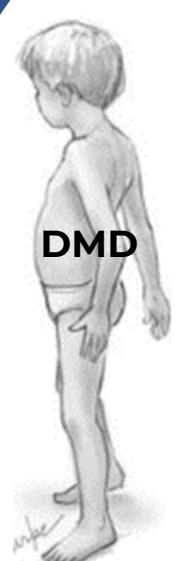
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## Workshop: Predictive simulations

### Case 1: Duchenne muscular dystrophy (DMD)

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DMD

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## Duchenne muscular dystrophy (DMD)

X-linked degenerative disorder

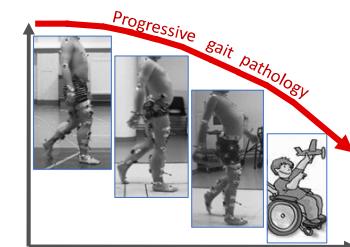
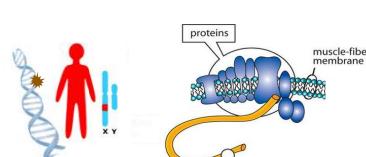
Absence of protein dystrophin

Muscle damage

Muscle impairments

- Progressive muscle weakness
- Progressive muscle stiffness and contractures

Progressive gait pathology



Sussman, 2002, J Am Acad Orthop Surg; Emery et al., 1991, Neuromuscul Disord; Sutherland et al., 1981, Develop. Med. Child. Neuro.

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## DMD case

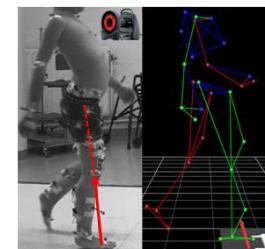
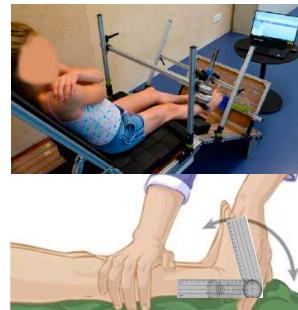
- Boy of 15.6 years
- Tiptoeing gait pattern



## Clinical assessments

### Weakness

- Fixed dynamometry



### Stiffness and contractures

- Clinical examination
  - Goniometry
  - Clinical stiffness scale

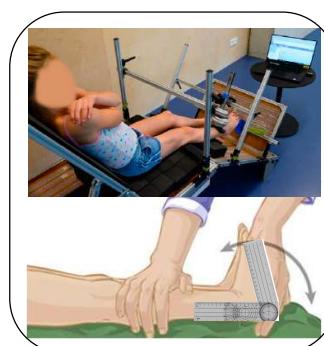
### Gait pattern

- 3D-gait analysis

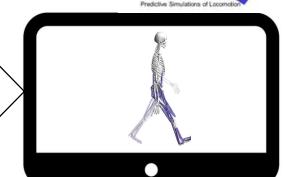
## Simulation approach

### Weakness

- Fixed dynamometry



Input

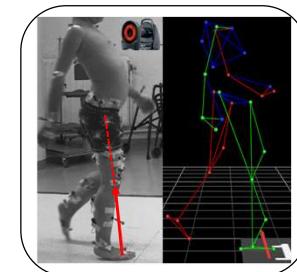


### Stiffness and contractures

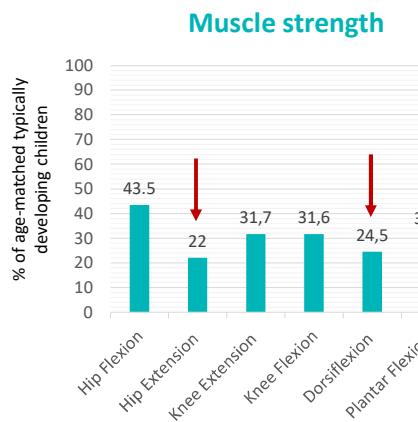
- Clinical examination
  - Goniometry
  - Clinical stiffness scale

### Gait pattern

- 3D-gait analysis



## DMD Case: muscle impairments



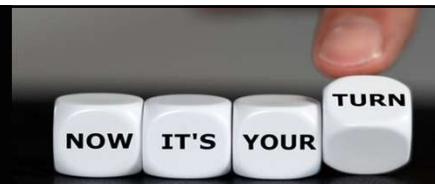
**Muscle stiffness/contractures**

	Range of motion	Clinical stiffness scale
Modified Thomas test	+5	2
True popliteal angle	-30	1
Silfverskold Test with knee extended	-20	3
Silfverskold Test with knee flexed in 90°	-10	2

## DMD Case: Achilles tendon lengthening

- Common in the past
- Later controversial
  - Some patients lost ambulation directly after Achilles tendon lengthening
- With predictive simulations based on personalized models, you can test whether such an intervention would improve the gait pattern





## 1. Model personalization

- Subject-specific muscle weakness
  - Based on instrumented strength scores
- Subject-specific muscle stiffness
  - Based on passive range of motion and clinical stiffness scale

## 2. Achilles tendon lengthening simulation

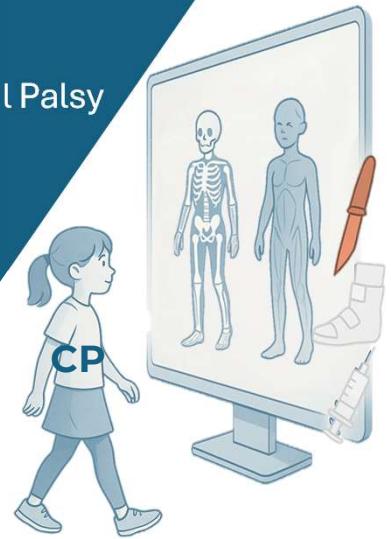
- Increase tendon slack length in the model
- Evaluate whether this intervention is appropriate for this patient

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# Workshop: Predictive simulations

Case 2: Surgical intervention for a child with Cerebral Palsy

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## Cerebral Palsy (CP)



### Motor control impairments

- Muscle weakness
- Joint hyper-resistance
- Reduced selective control

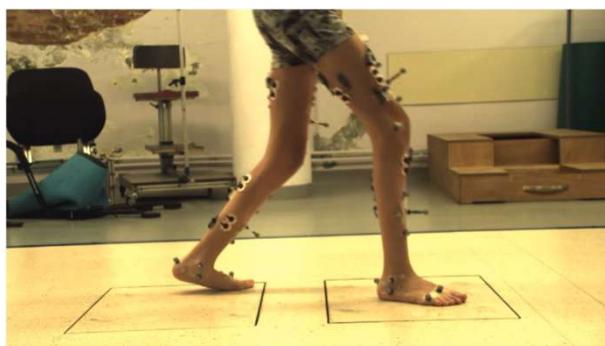


### Musculoskeletal impairments

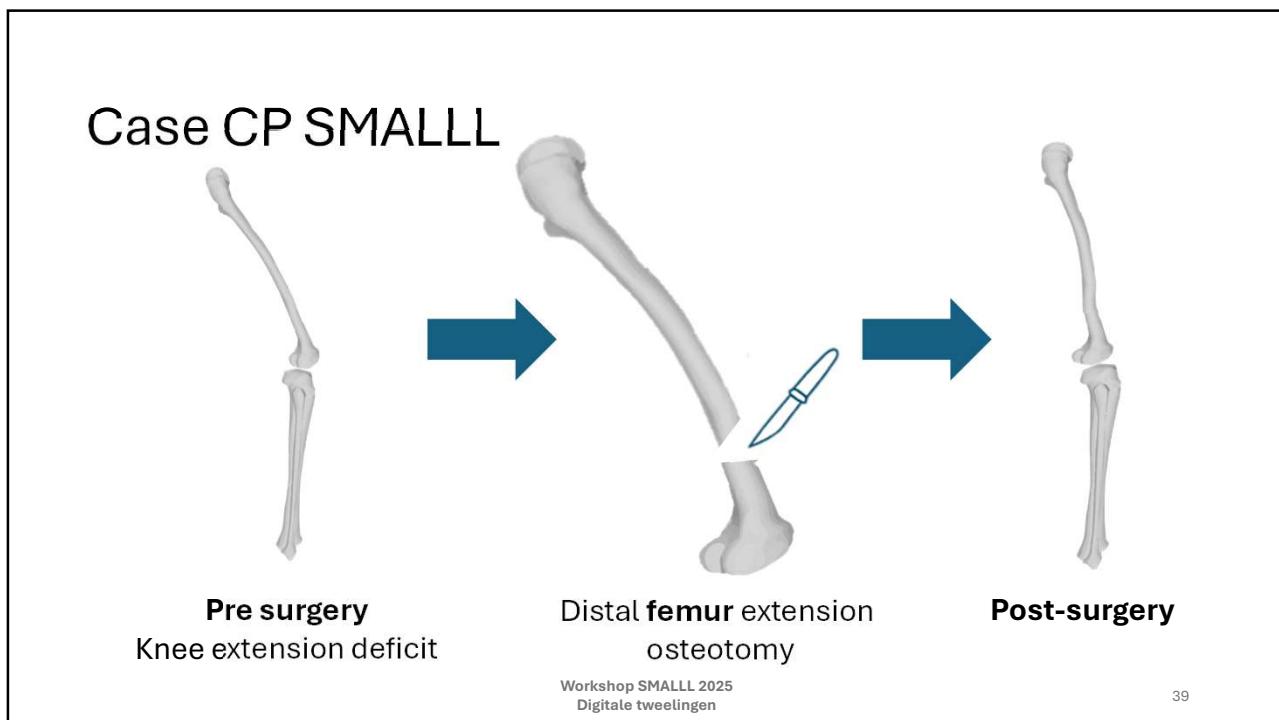


- Bony deformities
- Contractures

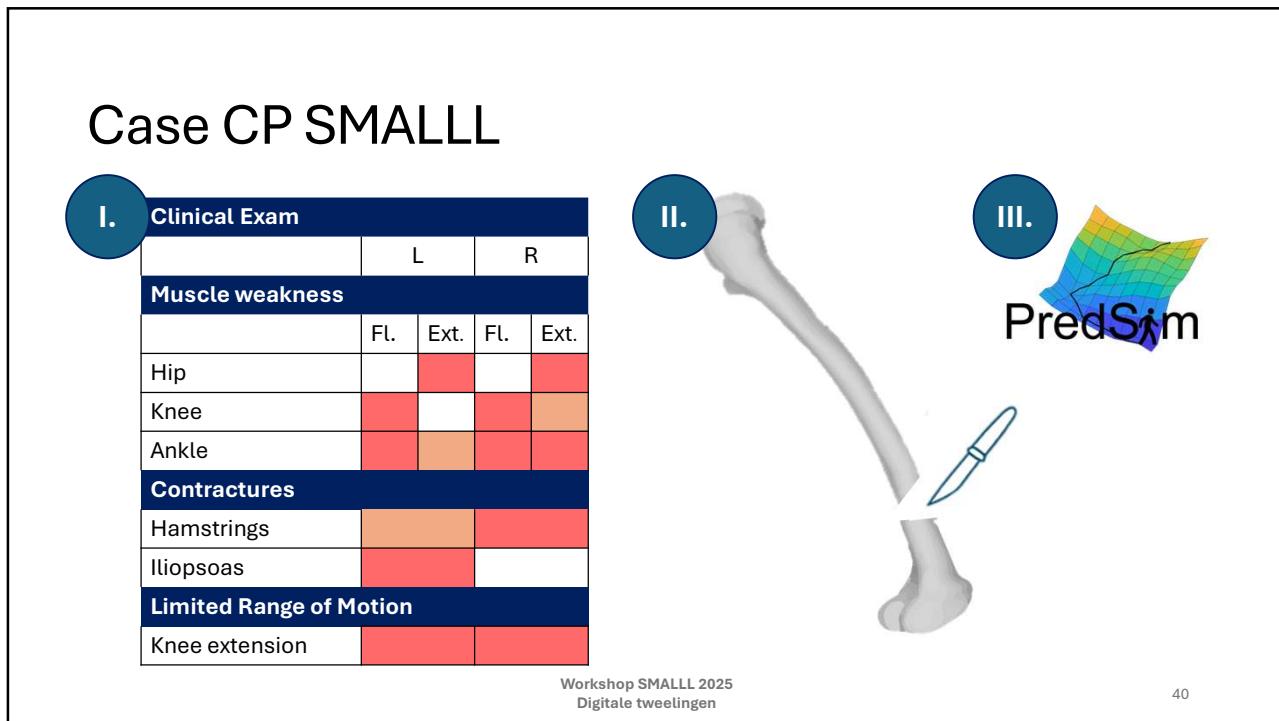
## Case CP SMALLL



Clinical Exam		L	R
<b>Muscle weakness</b>			
	Fl.	Ext.	Fl.
Hip			
Knee			
Ankle			
<b>Contractures</b>			
Hamstrings			
Iliopsoas			
Limited Range			
<b>Single Event Multilevel Surgery (SEMS)</b>			
Knee extension			



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## Workshop: Predictive simulations

Case 3: Simulate the effects of an ankle-foot orthosis on gait patterns in individuals with dropfoot

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## Case 3: footdrop / dropfoot (NL: klapvoet)

Common cause: nerve damage



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## Case 3: footdrop / dropfoot (NL: klapvoet)

Common cause: nerve damage



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## Case 3: footdrop / dropfoot (NL: klapvoet)

Common cause: nerve damage



Common treatment: ankle-foot orthosis (AFO)



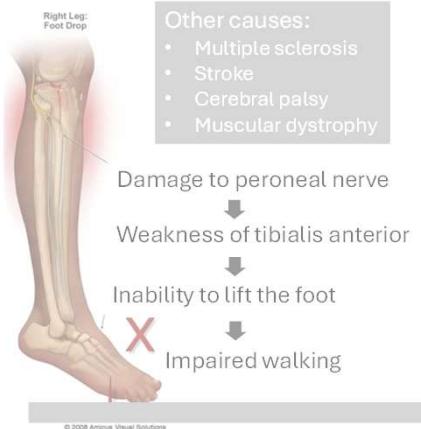
Stewart (2008), *Pract Neurol*, 8: 158–169

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## Case 3: footdrop / dropfoot (NL: klapvoet)

Common cause: nerve damage



Common treatment: ankle-foot orthosis (AFO)

Device properties:

- Rotational stiffness
- Neutral angle

Unclear which device properties are best

**Can we use predictive simulations to inform on AFO design?**



Stewart (2008), *Pract Neurol*, 8: 158–169

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## How to get started with the workshop



- Code sharing
- Documentation (“README”)

## How to get started with the workshop

### PredSim

<https://github.com/KULeuvenNeuromechanics/PredSim>



**Dependencies:** Windows,  
MATLAB, OpenSim, CasADI, Visual  
Studio, Cmake, Git

- Code sharing
- Documentation (“README”)

## Step 1: reference simulation with 2D model

### PredSim

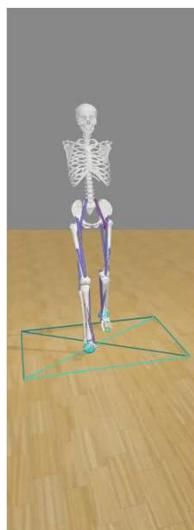


#### Running a reference 2D simulation with PredSim

Before going to the hands-on tutorials, the user should run a reference 2D simulation with [PredSim](#).

1. Open Matlab
2. Navigate to your `PredSim` folder in Matlab
3. Open the script `main.m` in Matlab by clicking on it
4. During this workshop the user will run predictive simulations with the 2D model instead of the default 3D model.  
Therefore, adjust the following lines in `main.m`:
  - o Line 20 - `[S] = initializeSettings('gait1018');`
  - o Line 25 - `S.subject.name = 'gait1018';`
5. Click on the green 'Run' button

## Step 1: reference simulation with 2D model



### Visualizing your simulation results in OpenSim

To visualize the simulation in OpenSim:

1. Open OpenSim
2. Click on 'File > Open Model...' and navigate to the 2D model `PredSim/Subjects/gait1018/gait1018.osim`
3. Click on 'File > Load Motion...' and navigate to the mot file of your simulation  
`PredSimResults/gait1018/gait1018_v1.mot`
4. Click on the 'Play forward' button to see the motion. You may also adapt the playback speed.

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## How to get started with the workshop

### PredSim

<https://github.com/KULeuvenNeuromechanics/PredSim>



**Dependencies:** Windows, MATLAB, OpenSim, CasADi, Visual Studio, Cmake, Git

- Code sharing
- Documentation ("README")

### Workshop

<https://github.com/KULeuvenNeuromechanics/PredSim-workshop-smalll-2025>



**Dependencies:** Windows, MATLAB, OpenSim, CasADi, Visual Studio, Cmake, Git

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## How to get started with the workshop

### Adding PredSim-workshop-smalll-2025 to path

Before starting one of the three cases, make sure that this repository is added to your Matlab path.

1. Either download or clone [the current repository](#)
2. Open Matlab
3. Navigate to the `PredSim-workshop-smalll-2025` folder
4. Open the script called `set_up_paths.m`
5. Click on the green 'Run' button

<https://github.com/KULeuvenNeuromechanics/PredSim-workshop-smalll-2025>

Workshop



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## Predictive simulations in 3D

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## Validation



PredSim

Predicted gait pattern

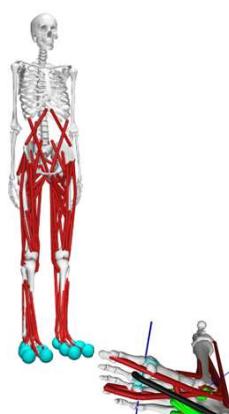
Experimental data

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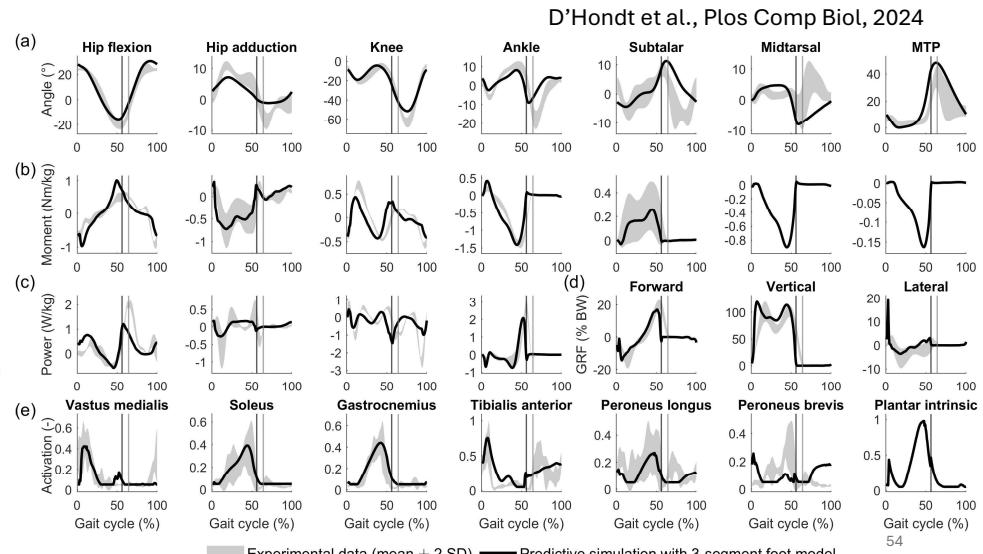
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## Simulations based on DHondt\_et\_al\_2024 capture walking pattern of unimpaired adult



Extended version of  
OpenSim's gait2392  
33 dofs  
94 muscles

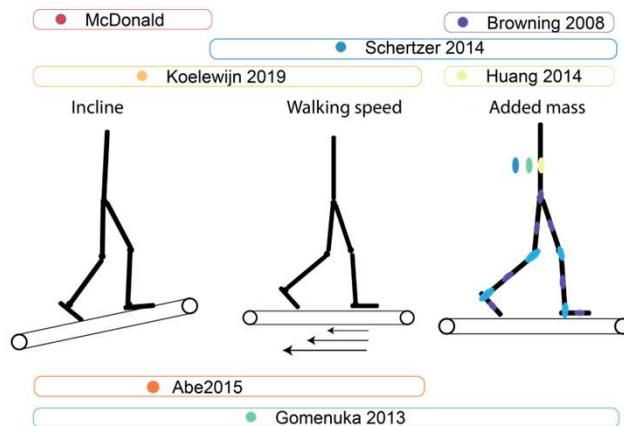


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## Do optimal control simulations predict gait mechanics and energetics across walking conditions?



Maarten Afschrift

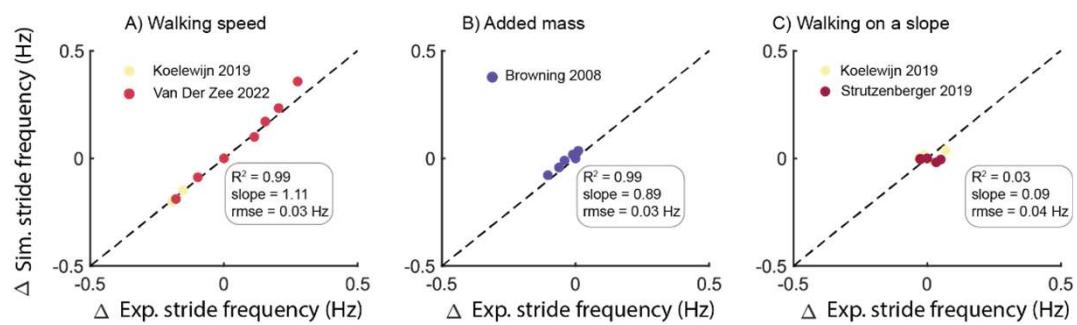


Falisse et al., *Plos One*, 2022; Afschrift et al., *bioRxiv*, 2025

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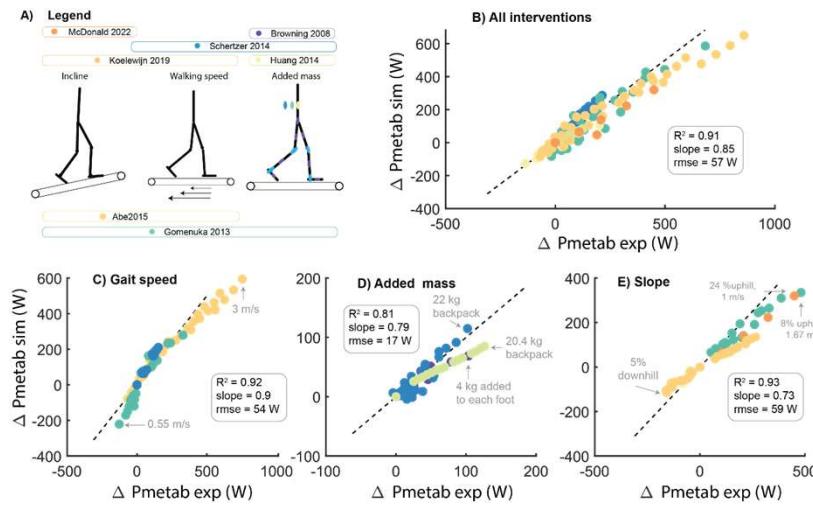
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## Simulations capture stride frequency across conditions



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## Optimal control simulations capture main trends but not fine details of healthy gait energetics



Overall, predictions of mechanics/activations are better than predictions of metabolic energy.

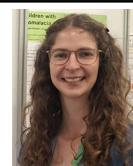
Afschrift et al., bioRxiv

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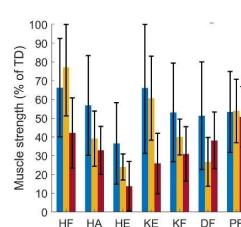
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## Contractures in Duchenne Muscular Dystrophy - Should we treat them or are they a useful compensation strategy?

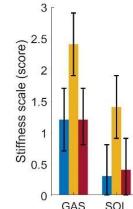


Ines Vandekerckhove

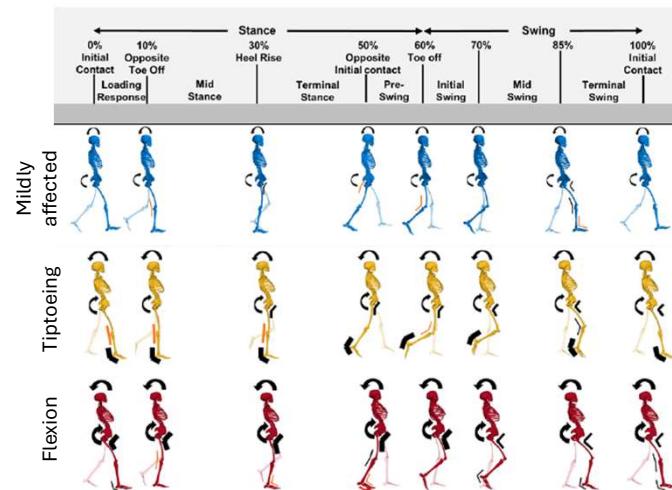
### WEAKNESS



### CONTRACTURES



Walking patterns based on a large longitudinal (30 boys – 137 measurements)



Vandekerckhove et al., Scientific Reports, 2024

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### Contractures in Duchenne Muscular Dystrophy

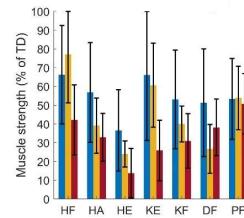
- Should we treat them or are they a useful compensation strategy?



WEAKNESS ONLY



Tiptoeing in the absence of contractures!



WEAKNESS AND CONTRACTURES

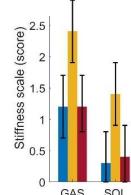
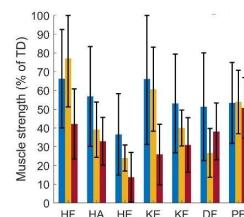


Vandekerckhove et al., JNER, 2025

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### Contractures in Duchenne Muscular Dystrophy

- Should we treat them or are they a useful compensation strategy?



Model could walk when we further increased weakness but not when we increased weakness and contractures.

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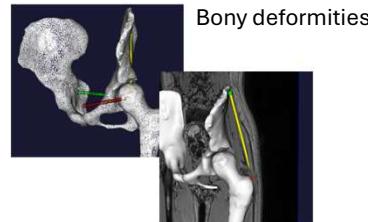
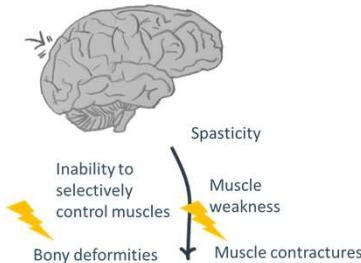
Vandekerckhove et al., JNER, 2025

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## What is the contribution of musculoskeletal deficits to alterations in gait kinematics in cerebral palsy?



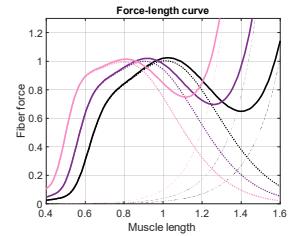
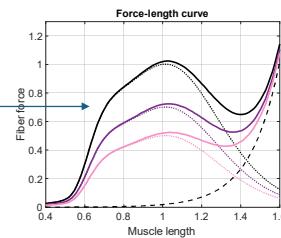
Bram Van Den Bosch



**CONTRACTURES** - Reduced optimal fiber length such that resistance torque at end of range of motion is 15Nm

Gait and balance impairments

**WEAKNESS** - Reduced maximal muscle force based on manual muscle testing score



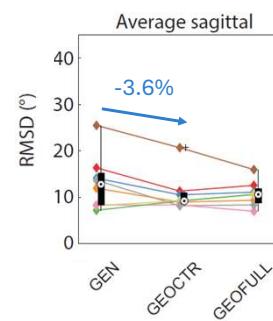
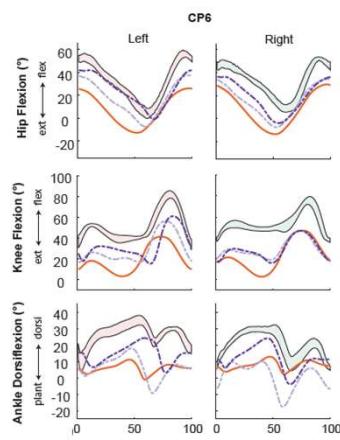
Van Den Bosch et al., *bioRxiv*, 2025

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## Modest and variable contributions of musculoskeletal impairments to alterations in gait kinematics in cerebral palsy



- In line with modest and variable improvements after multi-level surgery
- Remaining differences between simulated and experimental gait kinematics suggest large contribution of motor control impairments

Legend:  
 Left experimental ± SD (pink)  
 Right experimental ± SD (green)  
 Scaled generic model = GEN (orange)  
 Bony deformities + contractures = GEOCTR (blue dashed)  
 Bony deformities + contractures + weakness = GEOFULL (purple dashed)

Van Den Bosch et al., 2025

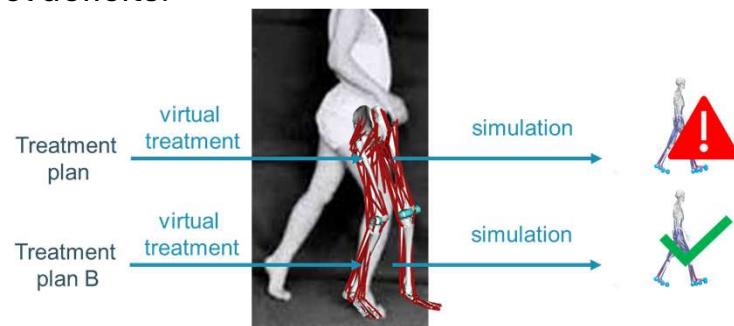
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We still need to demonstrate benefits of using predictive simulations for treatment selection and design

### Challenges

- Improve accuracy of simulations.
- Model motor control deficits.



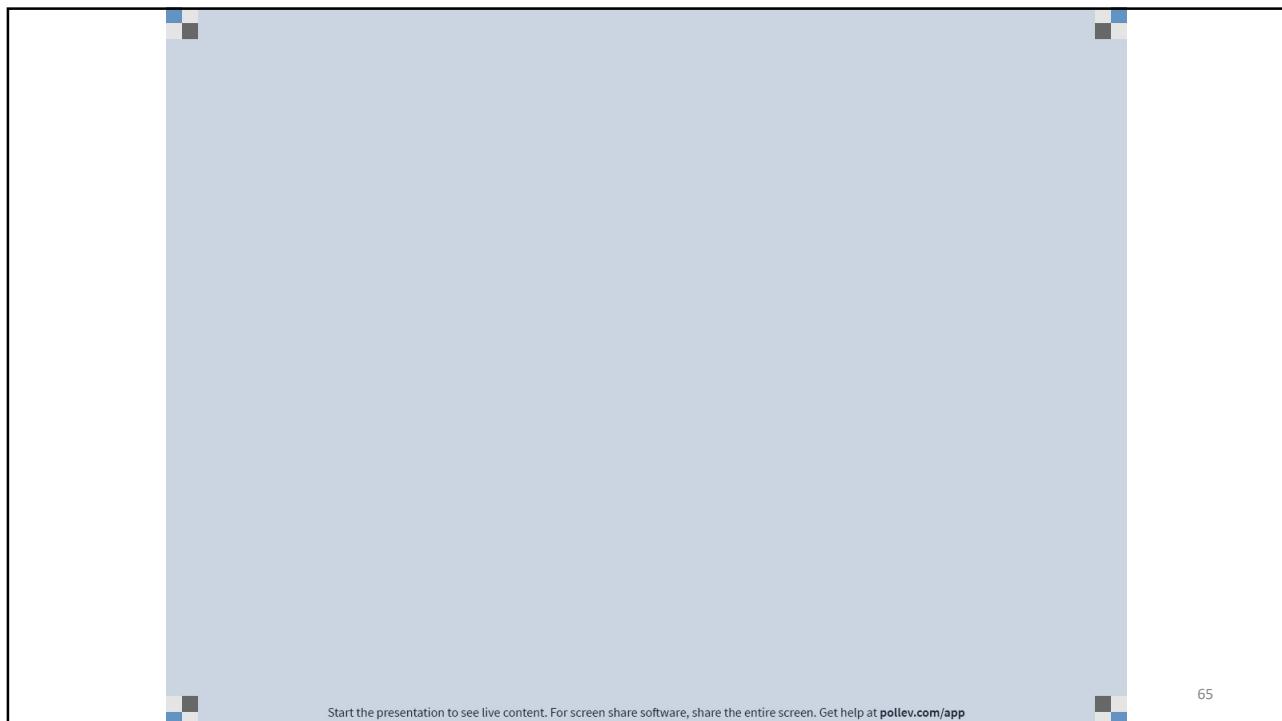
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## Kansen en obstakels voor de klinische implementatie van predictieve simulaties



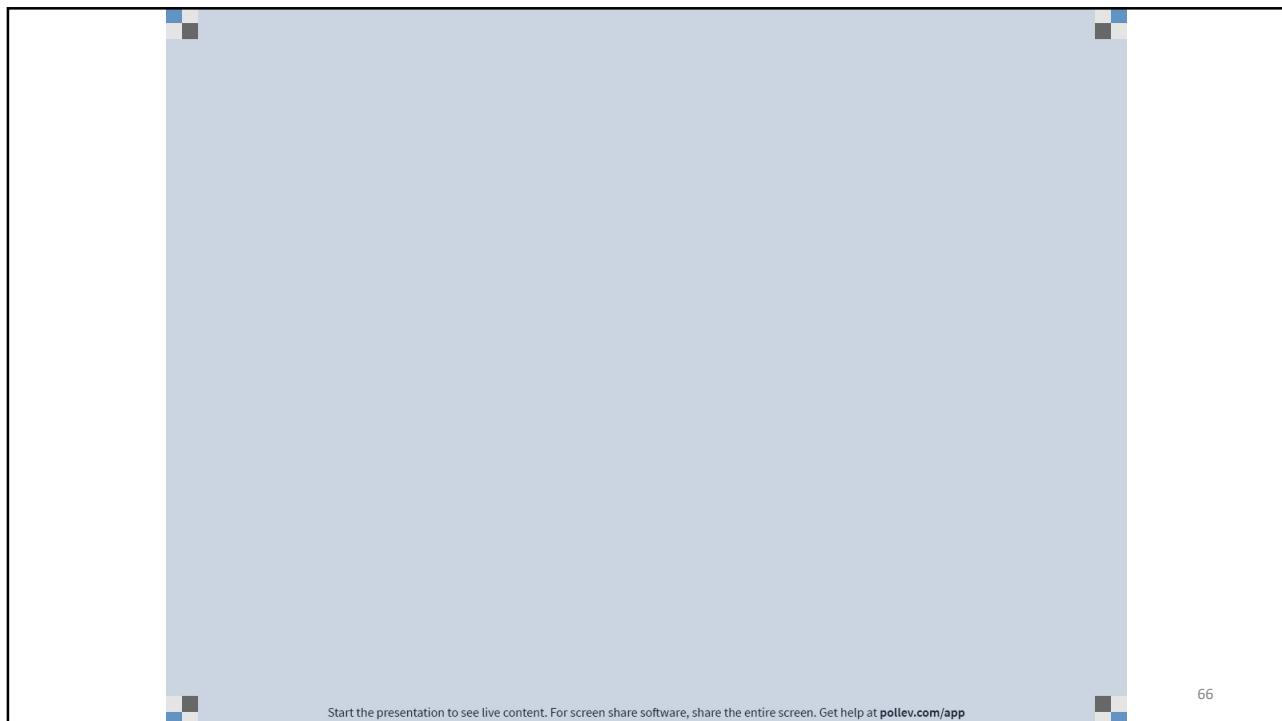
[PollEv.com/tombuurke748](https://PollEv.com/tombuurke748)



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## Het doel van vandaag

Nu...

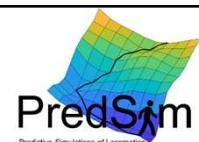
- kent u de onderliggende theorie van musculoskeletaal modelleren en predictieve simulaties.
- kunt u predictieve simulaties met 2D modellen in *PredSim* uitvoeren.
- kunt u de informatie en bronnen voor 3D simulaties vinden.
- kent u kansen en obstakels voor de klinische implementatie van predictieve simulaties.



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## Digitale tweelingen

**Predictieve simulaties van wandelen voor de klinische gangbeeldanalyse**

Tom Buurke, Friedl De Groote, Tim van der Zee, Ellis Van Can, Ines Vandekerckhove

Workshop SMALLL Congres 2025, Erasmus MC, Rotterdam, NL



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