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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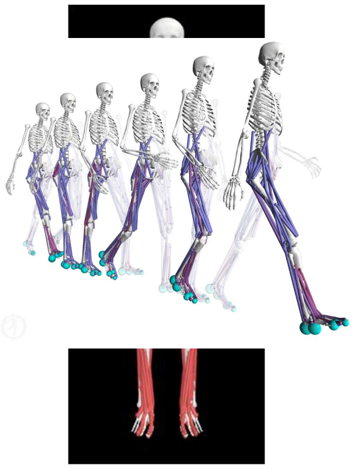
Predictieve simulaties van wandelen voor de klinische gangbeeldanalyse

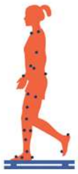
- Wat is een musculoskeletaal model?
  - Wiskundig model
  - Starre lichamen (botten)
  - Verbonden met gewrichten
  - Spieren over de gewrichten
  - Spieren genereren kracht en beweging



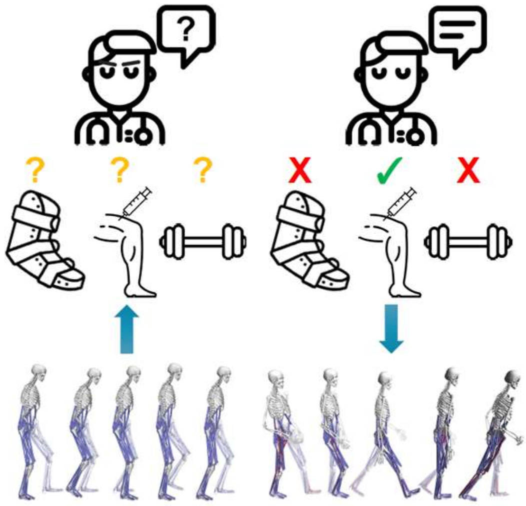
2

Waarom gebruiken we musculoskeletaal modellen?

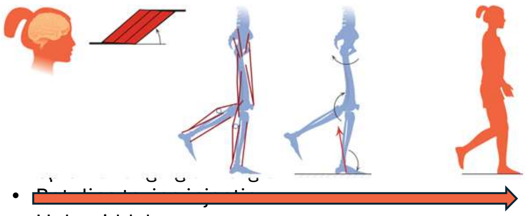
Vanuit gemeten data



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



De beweging voorspellen



-
-
  -
  - Hulpmiddelen

Illustrations from Uchida & Delp (2020)

Hoe gebruiken we musculoskeletaal modellen?

- Open-source software
  - OpenSim
  - PredSim
  - SCONE
  - Moco
  - MyoSuite
  - …
- Commercial software
  - Anybody
  - HyFyDy
  - …

- Simulation CPU time
  - 2001: 10,000 hours[1]
  - 2019: 1 hour[2]

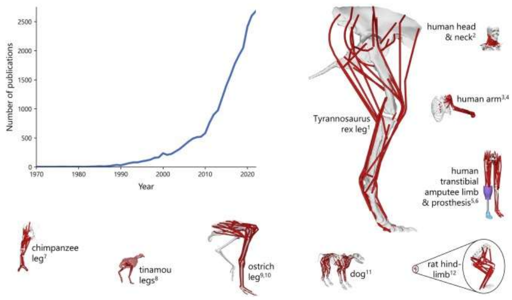


Figure from Uhlrich et al. (2023)

1) Anderson & Pandy (2001)
2) Falisse et al. (2019)


The musculoskeletal modelling landscape

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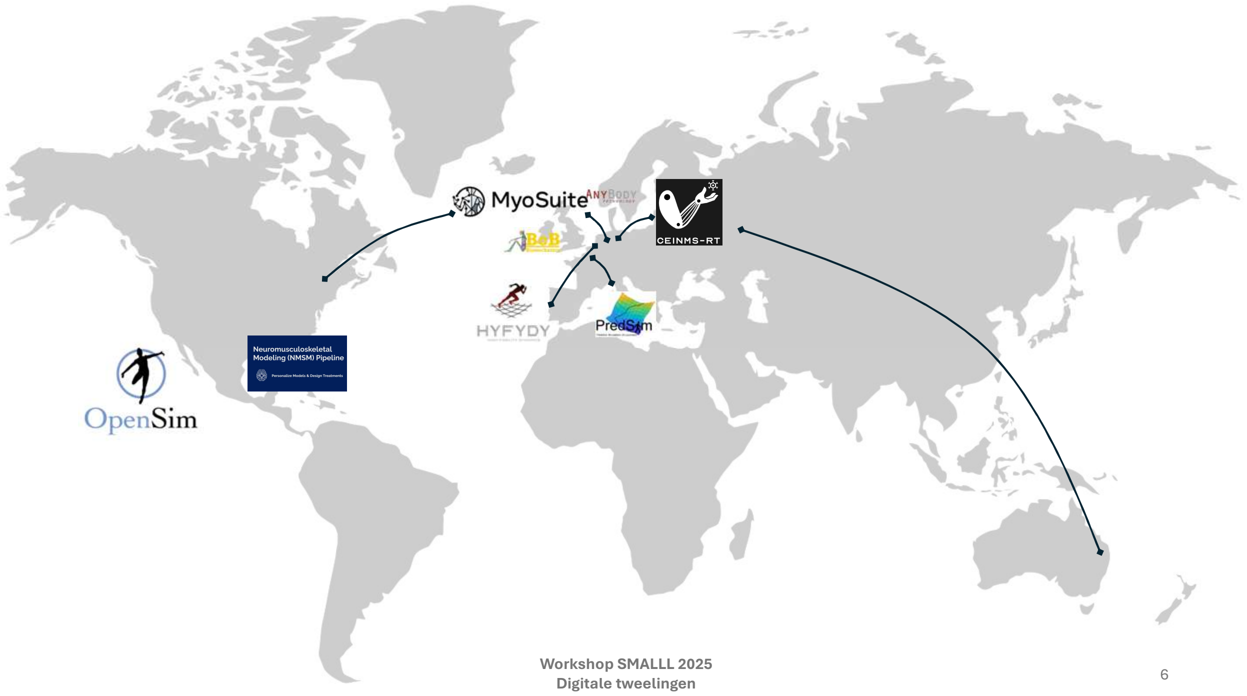
MyoSuite
ANYBODY
BoB
CEINMS-RT
HYFYDY
PredSim
Neuromusculoskeletal Modeling (NMSM) Pipeline
OpenSim

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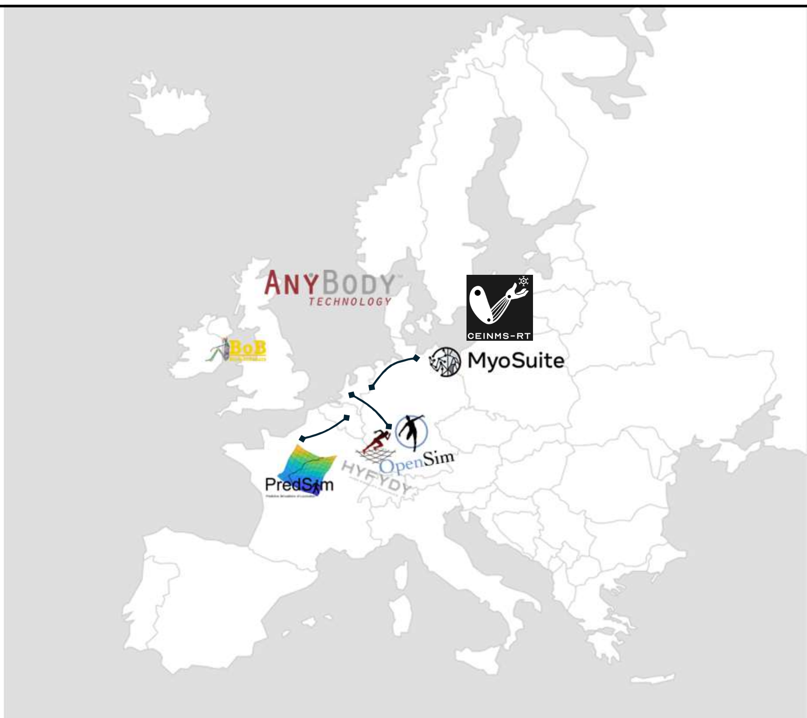


Het doel van vandaag

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.

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 Groote)

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)

PredSim
Predictive Simulations of Locomotion

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

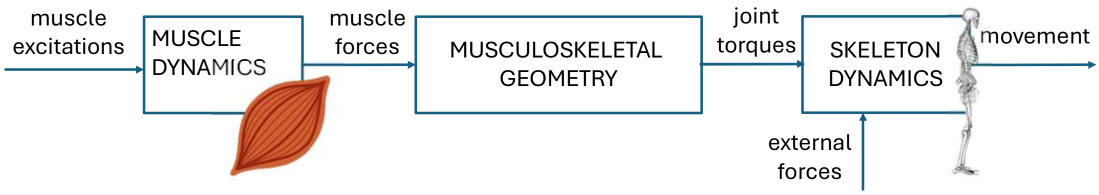
01:00 – 01:15: Afsluitende discussie

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

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

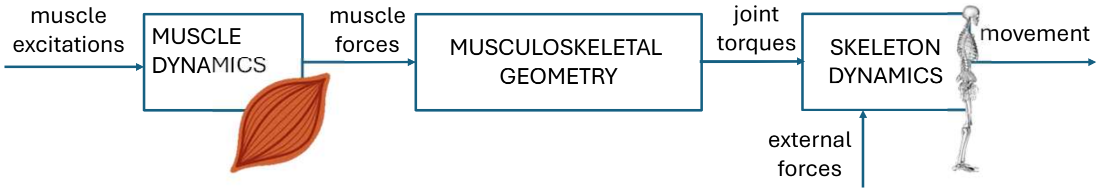
Optimal control assumption

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

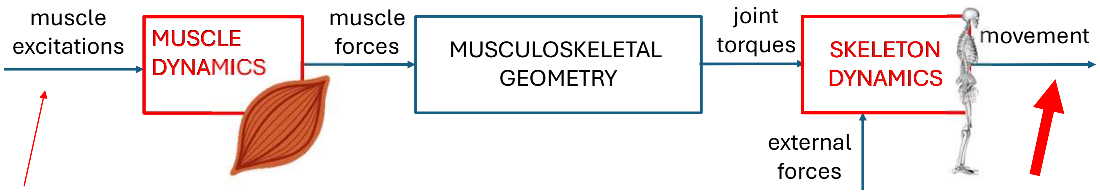
find muscle excitations **that**

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 Groote, 2019)

2001
2014
2018
2019

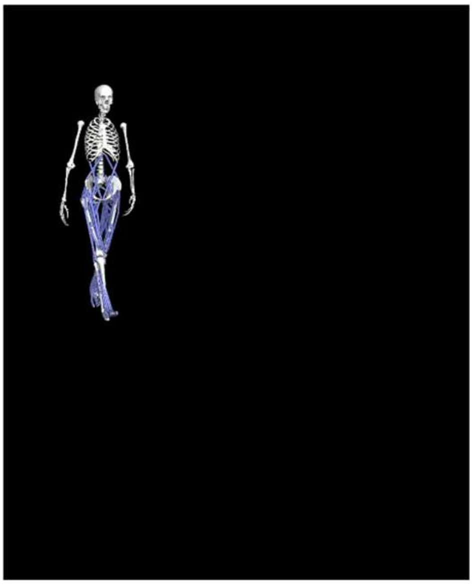
AUTOMATIC DIFFERENTIATION
IMPLICIT DYNAMICS
DIRECT COLLOCATION

PredSim

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

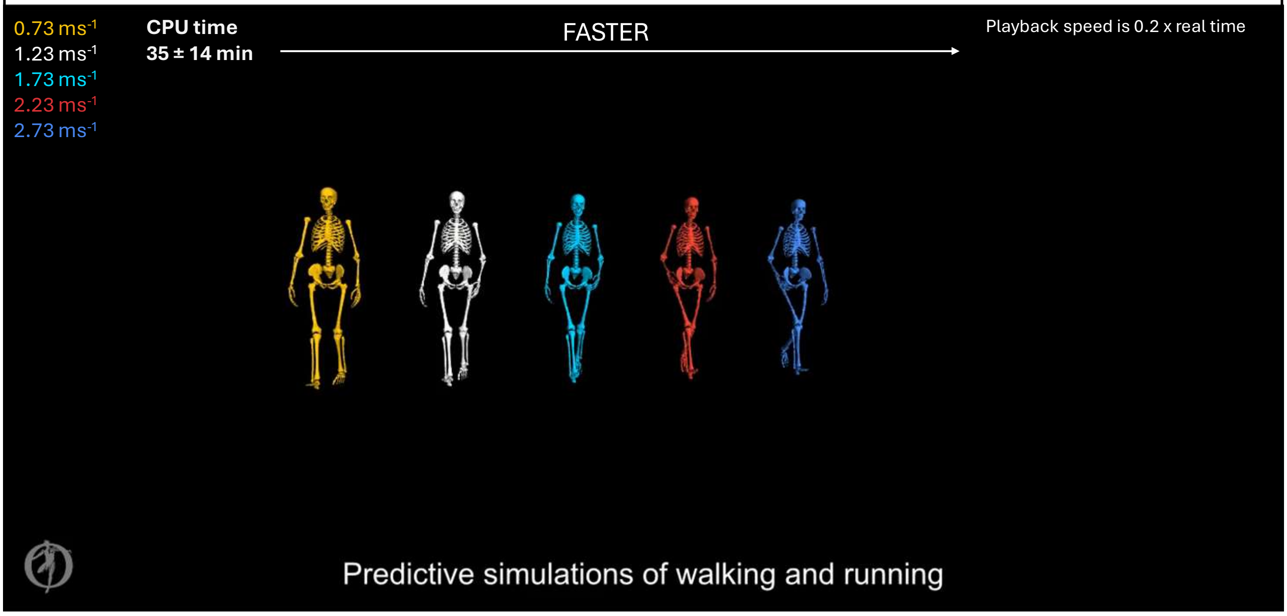
minimize cost →

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



Falisse et al., *J R Soc Interface,* 2019

Model predicts a continuum of walking and running gaits



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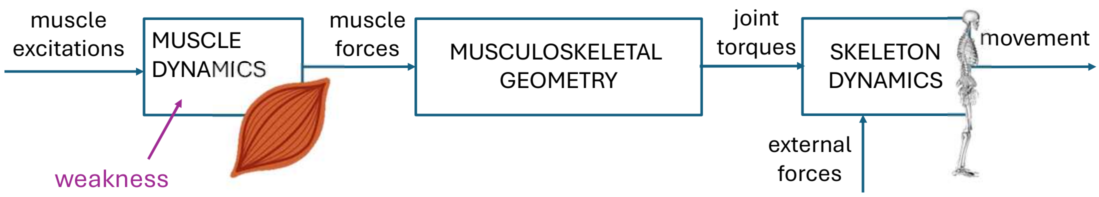
Modeling impairments

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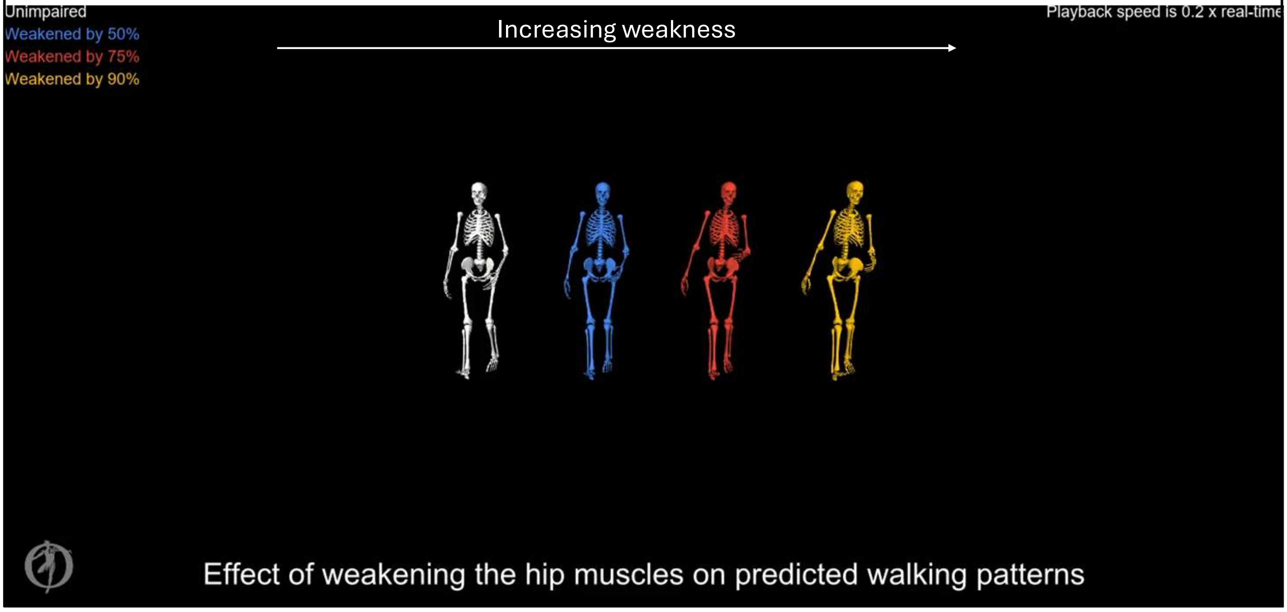
Decreased hip actuator strength led to compensated Trendelenburg (hip circumduction and trunk sway)



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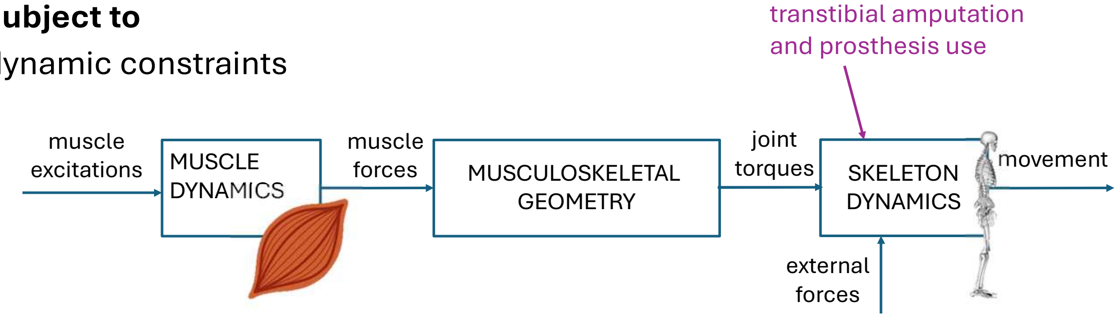
Modeling impairments

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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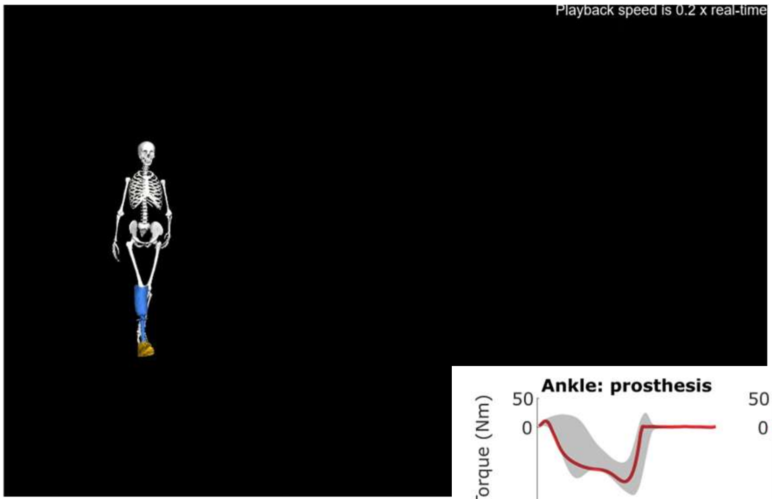
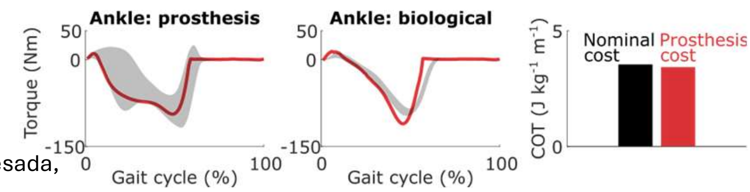
Prosthetic use altered the ankle torque in agreement with experimental data





Experimental data from Quesada, Caputo, Collins (2016)

PredSim

Muscle dynamics

Definition of optimal control problem

MATLAB

Skeleton dynamis using modified version of OpenSim that enables algorithmic differentiation

OpenSim

Musculoskeletal geometry

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

CasADi

https://web.casadi.org/

Why use PredSim software?

PredSim versus OpenSim Moco

	PredSim	**OpenSim Moco** (Dembia, Bianco et al. *PLOS COMP. BIOL.* 2020)
Simulation type	Predictive	Predictive, tracking or inverse
Task	Steady-state locomotion	Any task
Discretisation	Direct collocation	Direct collocation
Formulation of dynamics	Implicit	Implicit of 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)

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);
```

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

A few required settings ...

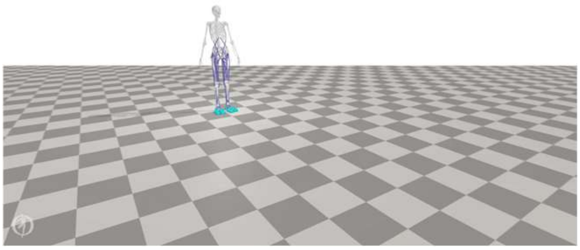
```
% Path to OpenSim model file
osim_path = './Subjects/Falisse_et_al_2022/Falisse_et_al_2022.osim';

% 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

… and many optional settings

- subject
- orthosis

This workshop

- metabolicEnergy
- weights
- solver
- bounds
- OpenSimADOptions
- post_processing
- misc (task constraints, file paths, scaling, …)

```
% 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

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.

PredSim

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Workshop: Predictive simulations

Case 1: Duchenne muscular dystrophy (DMD)

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Duchenne muscular dystrophy (DMD)

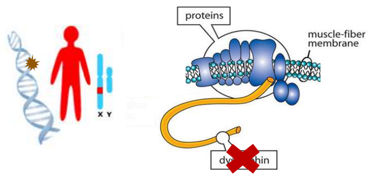
X-linked degenerative disorder

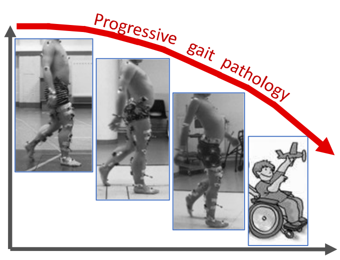
Absence of protein dystrophin

Muscle damage

Muscle impairments
- ➢ Progressive muscle weakness
- ➢ Progressive muscle stiffness and contractures

Progressive gait pathology





Sussman, 2002, J Am Acad Orhtop 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

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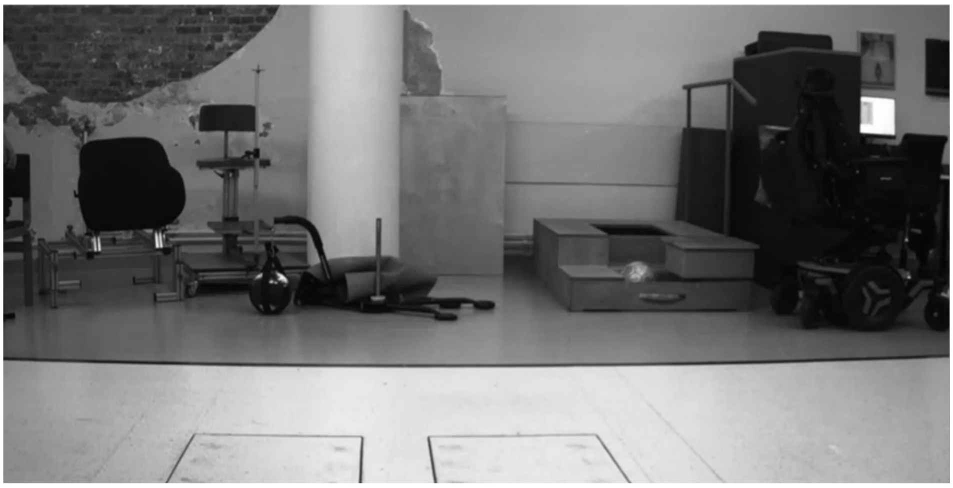

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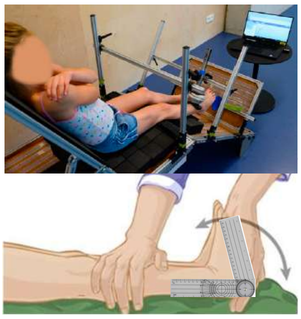
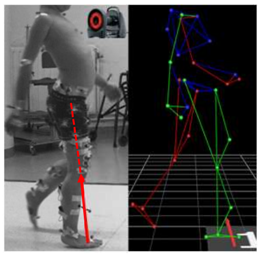
Clinical assessments

Weakness
- Fixed dynamometry

Stiffness and contractures
- Clinical examination
  - Goniometry
  - Clinical stiffness scale

Gait pattern
- 3D-gait analysis





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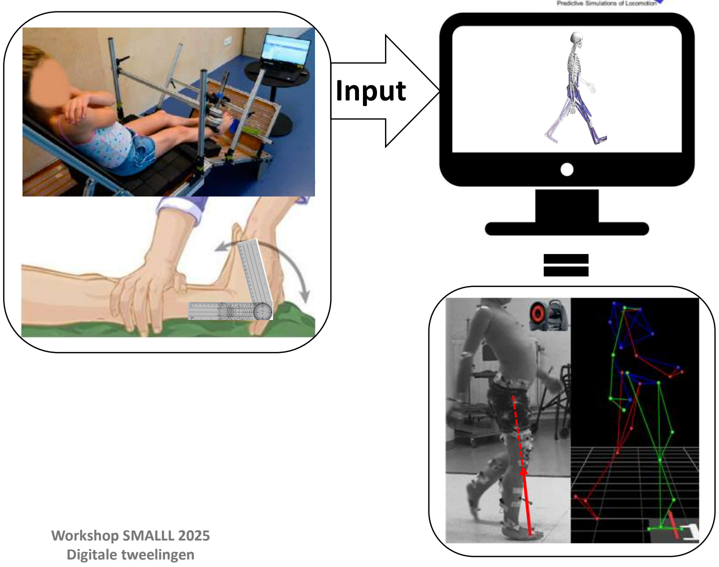
Simulation approach

PredSim

Weakness
- Fixed dynamometry

Stiffness and contractures
- Clinical examination
  - Goniometry
  - Clinical stiffness scale

Gait pattern
- 3D-gait analysis



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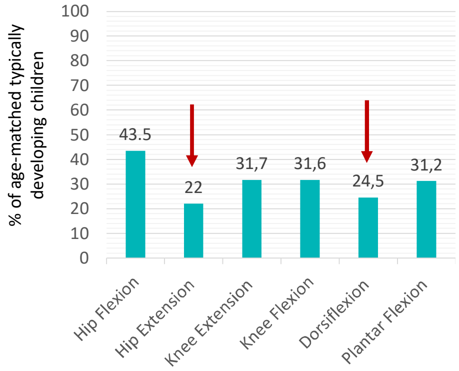
DMD Case: muscle impairments

Muscle strength

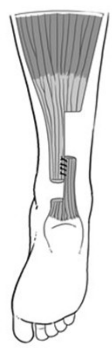


Muscle stiffness/contractures

	Range of motion	Clinical stiffness scale
Modified Thomas test	+5	2
True popliteal angle	-30	1
Silfversköld Test with knee extended	-20	3
Silfversköld 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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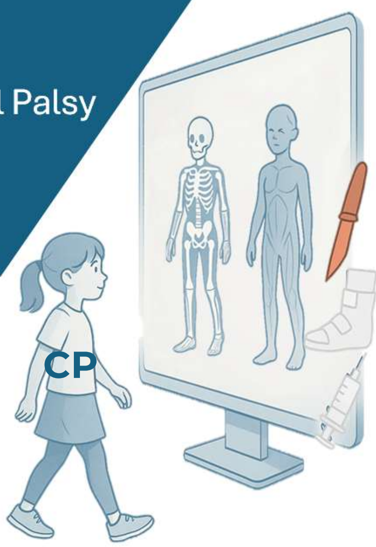
Workshop: Predictive simulations

Case 2: Surgical intervention for a child with Cerebral Palsy



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Cerebral Palsy (CP)

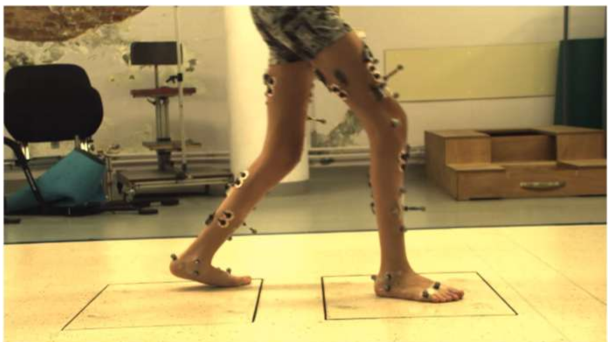
Motor control impairments

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

Musculoskeletal impairments

- Bony deformities
- Contractures

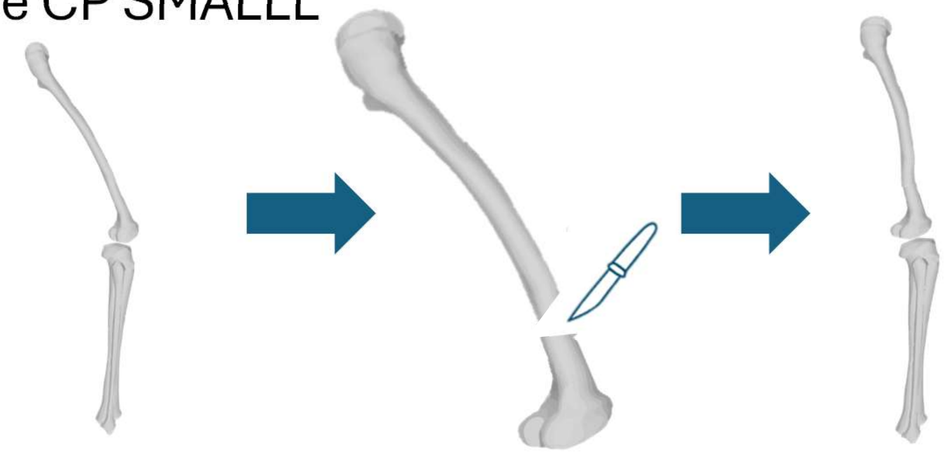
Case CP SMALLL



Clinical Exam				
	L		R	
Muscle weakness				
	Fl.	Ext.	Fl.	Ext.
Hip				
Knee				
Ankle				
Contractures				
Hamstrings				
Iliopsoas				
Limited Range				
Knee extension				

Single Event Multilevel Surgery (SEMS)

Case CP SMALLL



Pre surgery
Knee extension deficit

Distal **femur** extension osteotomy

Post-surgery

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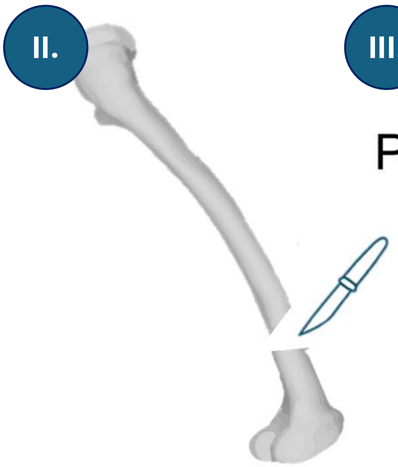
Case CP SMALLL

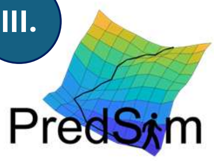
I.

Clinical Exam				
	L		R	
Muscle weakness				
	Fl.	Ext.	Fl.	Ext.
Hip				
Knee				
Ankle				
Contractures				
Hamstrings				
Iliopsoas				
Limited Range of Motion				
Knee extension				

II.



III.



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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

Other causes:
- Multiple sclerosis
- Stroke
- Cerebral palsy
- Muscular dystrophy

Damage to peroneal nerve

Inability to lift the foot

Case 3: footdrop / dropfoot (NL: klapvoet)

Common cause: nerve damage

Other causes:
- Multiple sclerosis
- Stroke
- Cerebral palsy
- Muscular dystrophy

Damage to peroneal nerve
↓
Weakness of tibialis anterior
↓
Inability to lift the foot
↓
Impaired walking

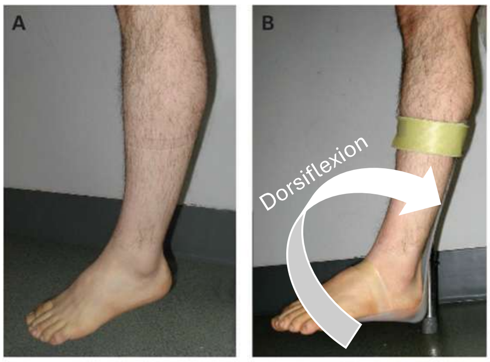
Case 3: footdrop / dropfoot (NL: klapvoet)

Common cause: nerve damage

Other causes:
- Multiple sclerosis
- Stroke
- Cerebral palsy
- Muscular dystrophy

Damage to peroneal nerve
↓
Weakness of tibialis anterior
↓
Inability to lift the foot
↓
Impaired walking

Common treatment: ankle-foot orthosis (AFO)



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

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

How to get started with the workshop

GitHub

- Code sharing
- Documentation (“README”)

How to get started with the workshop

PredSim

https://github.com/KULeuvenNeuromechanics/PredSim

GitHub

- Code sharing
- Documentation ("README")

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

Step 1: reference simulation with 2D model

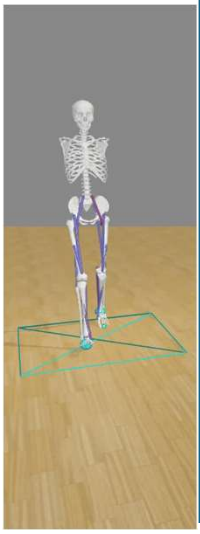
PredSim

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` :
   - Line 20 - `[S] = initializeSettings('gait1018');`
   - Line 25 - `S.subject.name = 'gait1018';`
5. Click on the green 'Run' button

Step 1: reference simulation with 2D model



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

How to get started with the workshop

PredSim

https://github.com/KULeuvenNeuromechanics/PredSim

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

- Code sharing
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Workshop

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How to get started with the workshop

Adding PredSim-workshop-smalll-2025 to path

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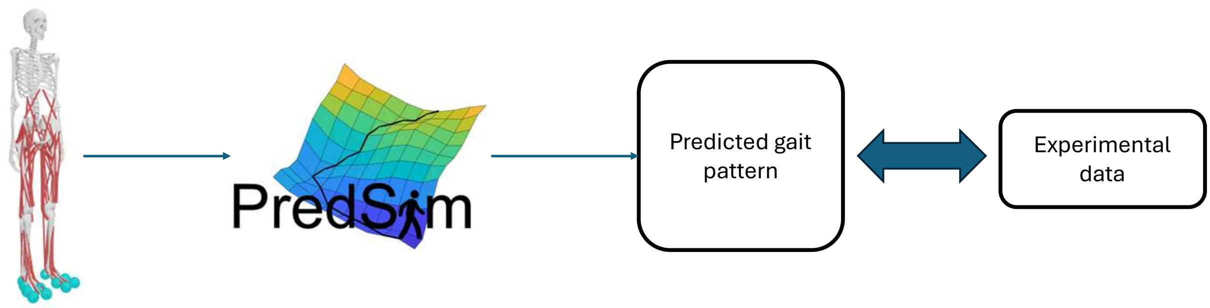
5. Click on the green 'Run' button

Workshop

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

Predictive simulations in 3D

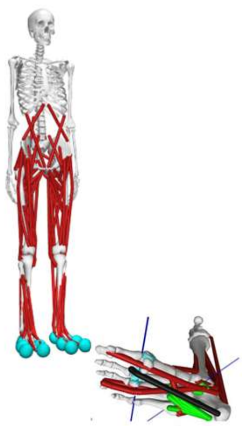
Validation



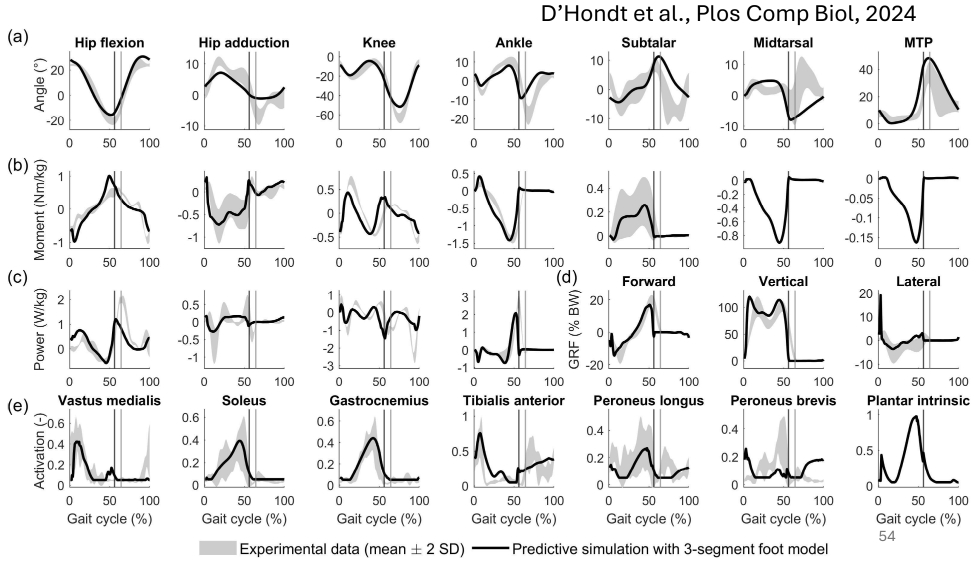
53

Simulations based on DHondt_et_al_2024 capture walking pattern of unimpaired adult

D'Hondt et al., Plos Comp Biol, 2024



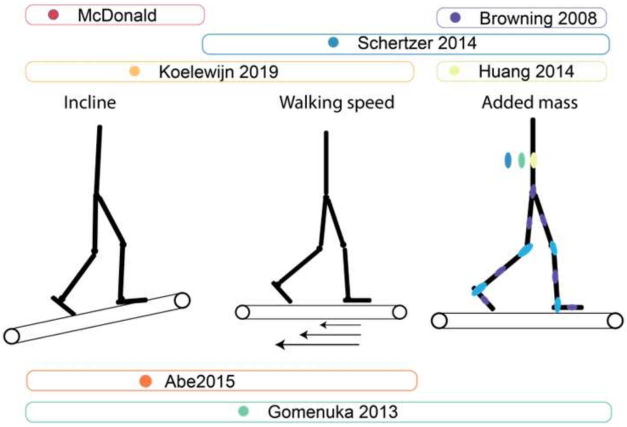
Extended version of
OpenSim's gait2392
33 dofs
94 muscles



54

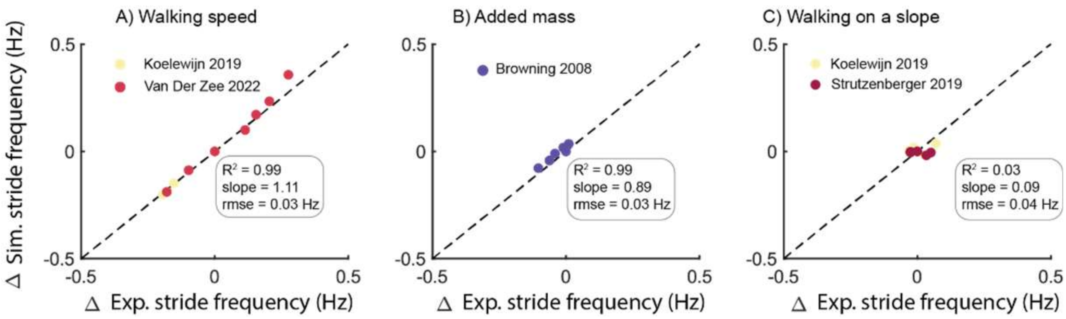
Do optimal control simulations predict gait mechanics and energetics across walking conditions?

Maarten Afschrift



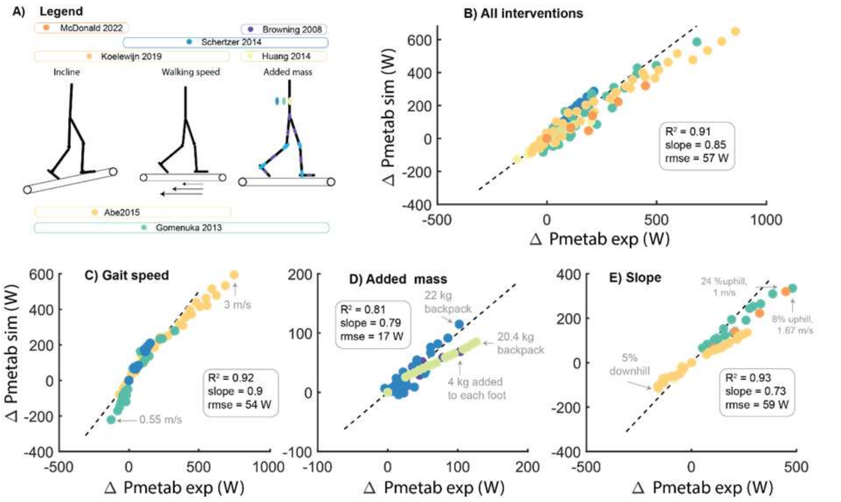
Falisse et al., *Plos One*, 2022; Afschrift et al., *bioRxiv*, 2025

Simulations capture stride frequency across conditions



Afschrift et al., bioRxiv

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



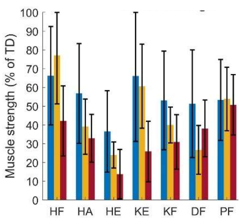
Overall, predictions of mechanics/ activations are better than predictions of metabolic energy.

Afschrift et al., bioRxiv

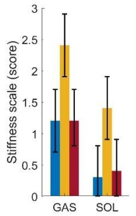
Contractures in Duchenne Muscular Dystrophy
- Should we treat them or are they a useful compensation strategy?

Ines Vandekerckhove

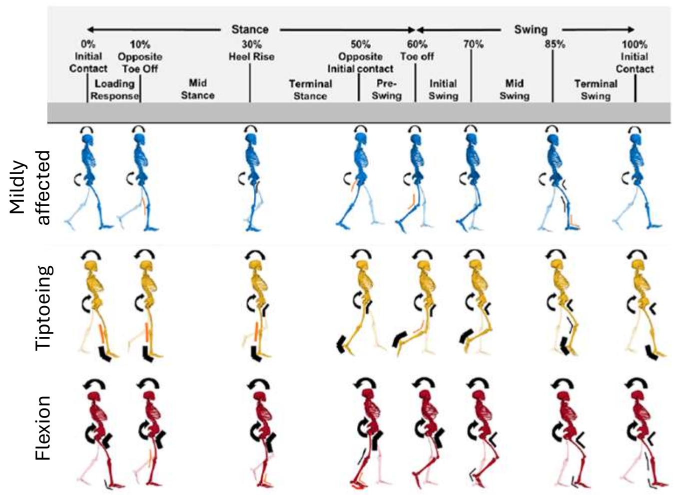
WEAKNESS



CONTRACTURES

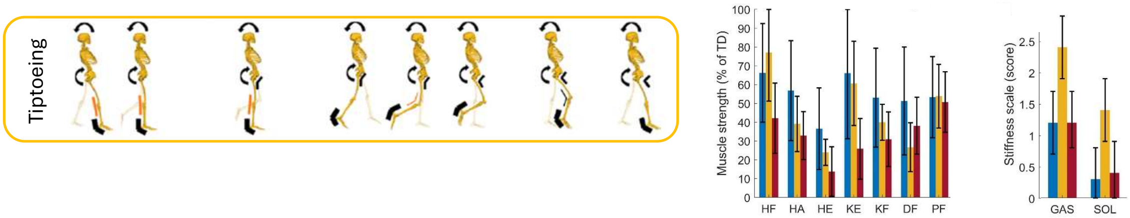


Walking patterns based on a large longitudinal (30 boys – 137 measurements)



Vandekerckhove et al., Scientific Reports, 2024

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



WEAKNESS ONLY

WEAKNESS AND CONTRACTURES

Tiptoeing in the absence of contractures!

Vandekerckhove et al., JNER, 2025

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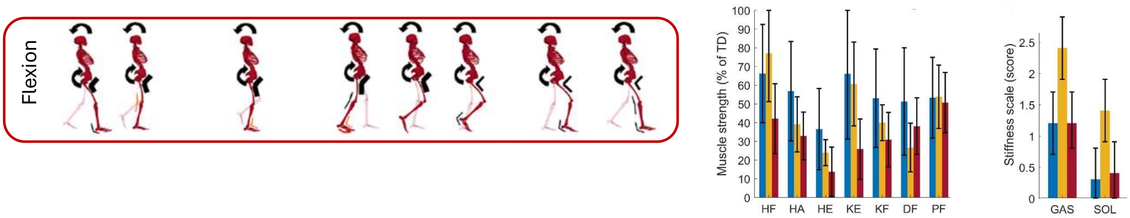
Contractures in Duchenne Muscular Dystrophy
- Should we treat them or are they a useful compensation strategy?



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

Vandekerckhove et al., JNER, 2025

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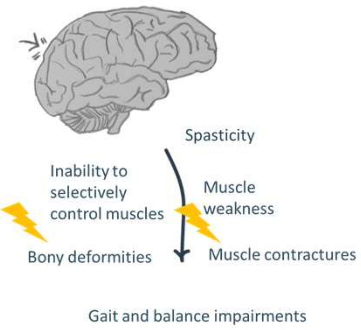
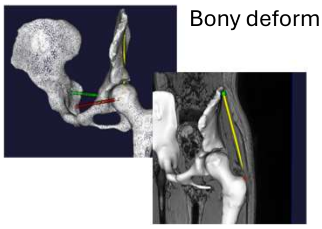
What is the contribution of musculoskeletal deficits to alterations in gait kinematics in cerebral palsy?



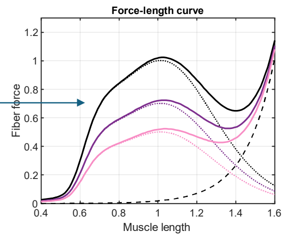


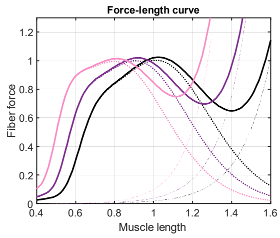
Bony deformities

Bram Van Den Bosch

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

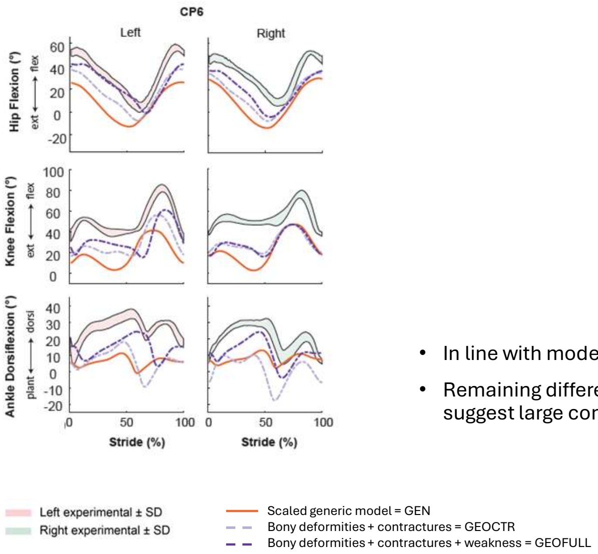
WEAKNESS - Reduced maximal muscle force based on manual muscle testing score

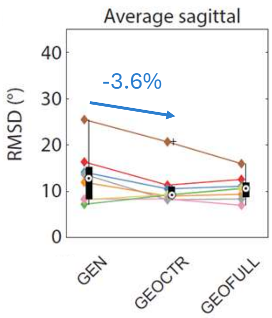




Van Den Bosch et al., *bioRxiv*, 2025

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





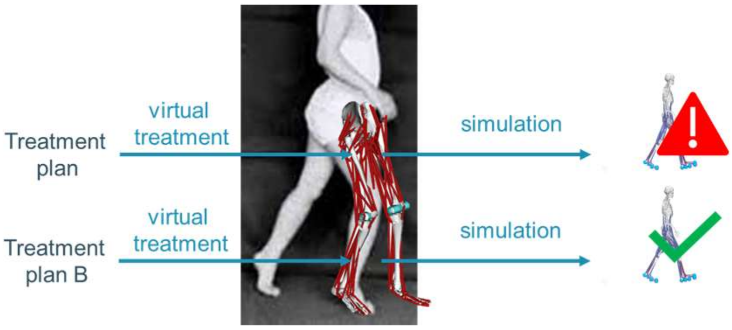
- In line with modest and variable improvements after multi-level surgery
- Remaining differences between simulated and experimental gait kinematics suggest large contribution of motor control impairments

Van Den Bosch et al., 2025

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

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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.

PredSim
Predictive Simulations of Locomotion

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

umcg SMALLL KU LEUVEN