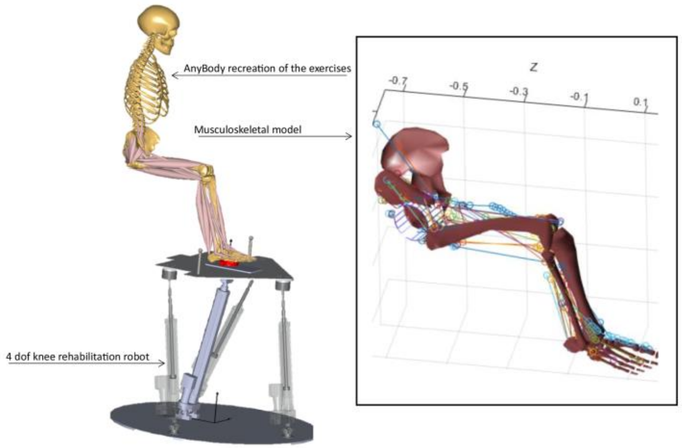
January 25, 2024

Validation of a real-time musculoskeletal model with AnyBody

Resolution of the inverse dynamics of musculoskeletal model of the lower limb validated with AnyBody



The webcast will begin shortly...

Outline

- Introduction to the AnyBody Modeling System
- Presentation by Pau Zamora Ortiz
  - Validation of a real-time musculoskeletal model with AnyBody
- Upcoming AnyBody events
- Question and answer session

Presenter

Pau Zamora Ortiz

Researcher in Biomechanical Engineering

Polytechnic University of Valencia

Host

Kristoffer Iversen

Technical Sales Executive

AnyBody Technology

Control Panel

The Control Panel appears on the right side of your screen.

Submit questions and comments via the Questions panel.

Questions will be addressed at the end of the presentation. If your question is not addressed, we will do so by email.

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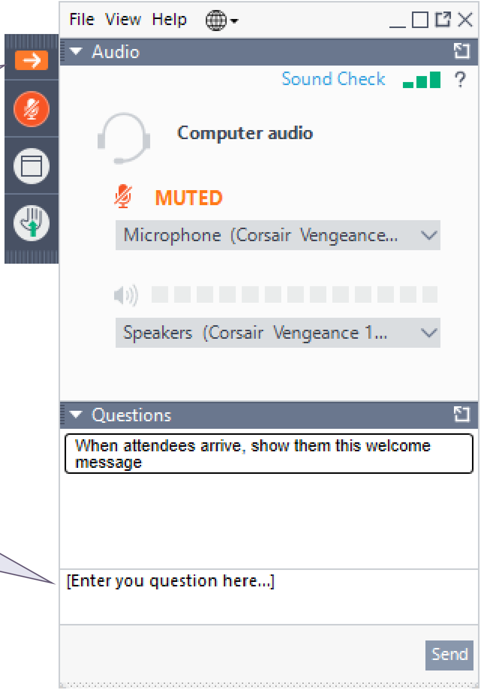
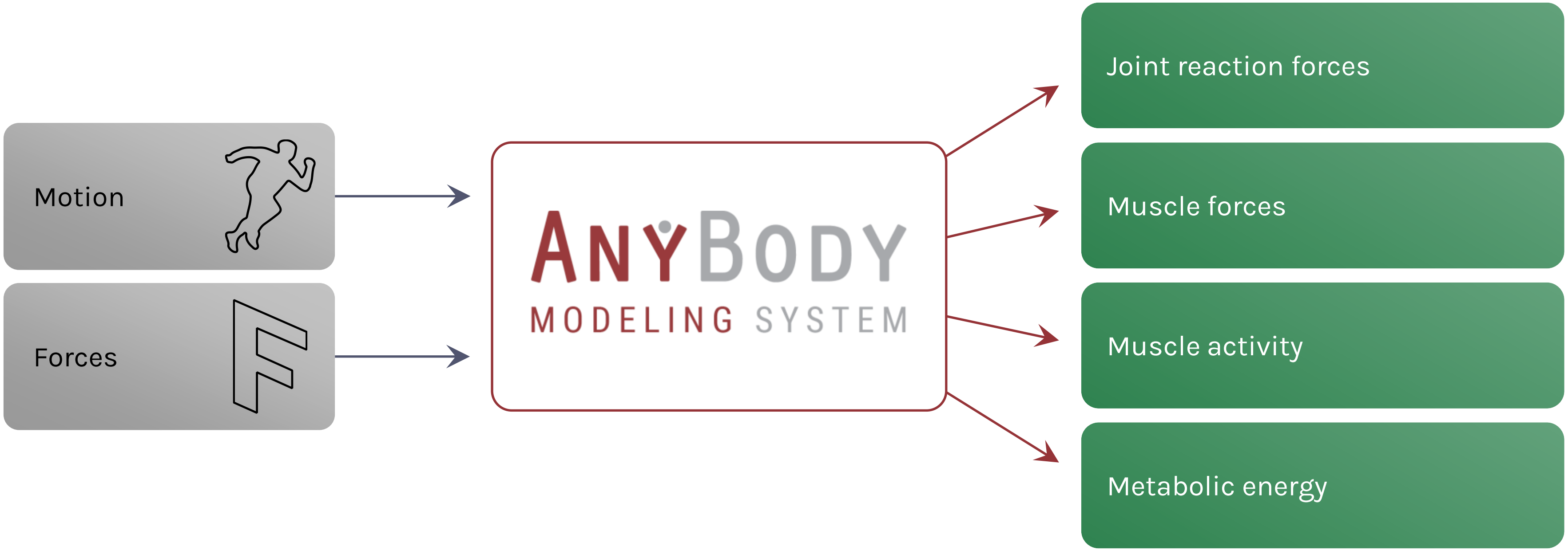
Ask a question during the presentation



Musculoskeletal simulations

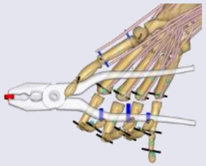
INPUT • Motion data

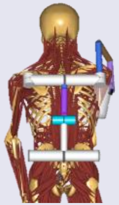
OUTPUT • Internal Body Loads



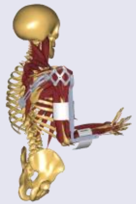
Motion analysis

Product design and optimization

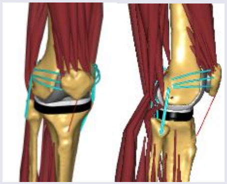




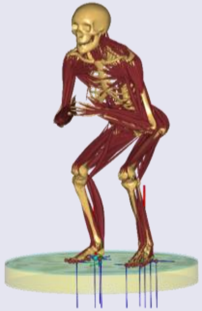
Ergonomics with/without exoskeletons



ANYBODY MODELING SYSTEM



Orthopedics and Rehabilitation



Sports

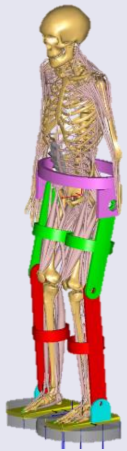
Automotive

Workflow

Motions and forces

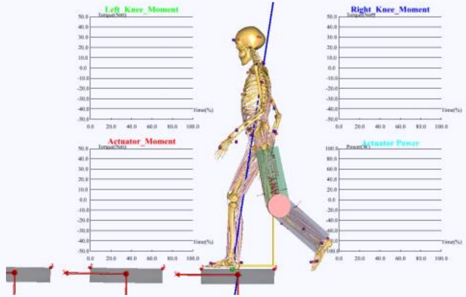
Body model

Environment model



Simulation

Inverse dynamics
Muscle recruitment



Internal body loads:

- Muscle forces
- Joint forces

Design Optimization

Post Processing
(e.g. Finite Element tools)

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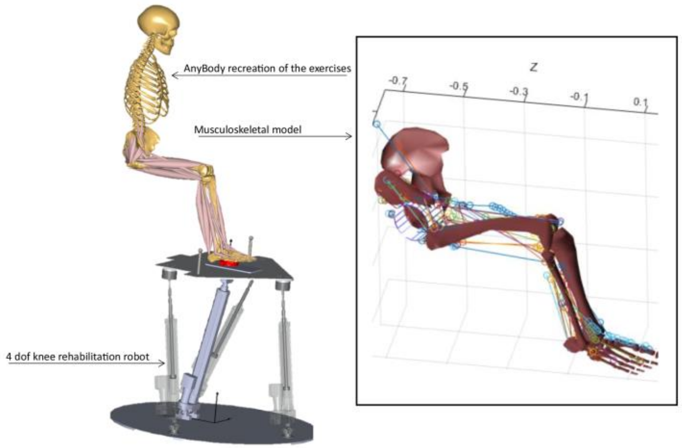
Resolution of the inverse dynamics of musculoskeletal model of the lower limb validated with AnyBody



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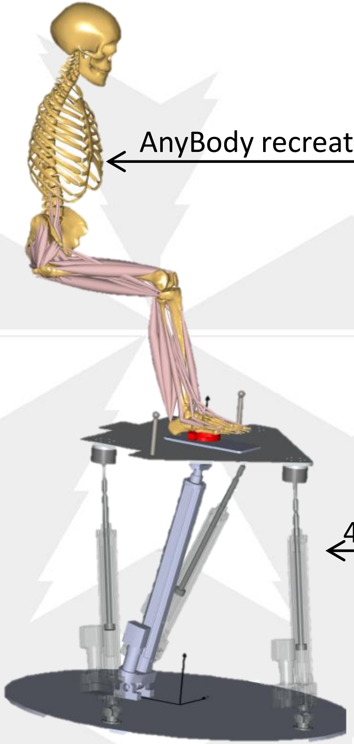
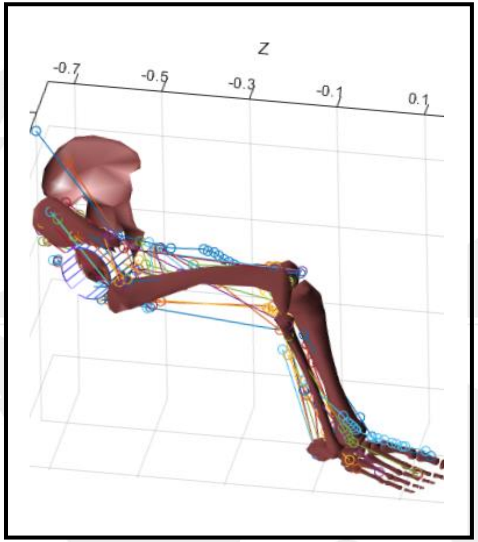
Validation of a real-time musculoskeletal model with AnyBody



AnyBody recreation of the exercises

4 dof knee rehabilitation robot

Real-time Musculoskeletal model



Autor: **Pau Zamora Ortiz**

January 2024

ÍNDICE

1

Introduction

- Objectives.

Objectives

1

Lower limb musculoskeletal model

Development of a lower limb model to be used in conjunction with the knee rehabilitation robot.

2

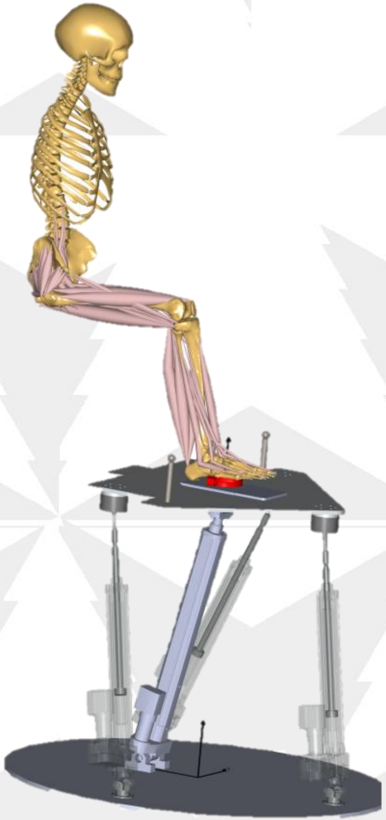
Model validation

Model validation process by comparing its results with data from other models and empirical data and robustness analysis of the model components.

3

Development of rehabilitation tools

Development of the force envelope for the estimation of the maximum force.
Calculation of the equivalent external force for the desired muscle activation.



2

REAL-TIME MODEL

- Model characteristics.
- Kinematics.
- Dynamics.
- Muscle resolution.

Model characteristics

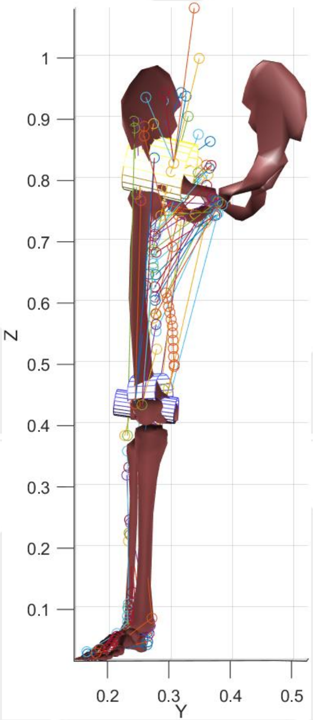
6 Degree of freedom

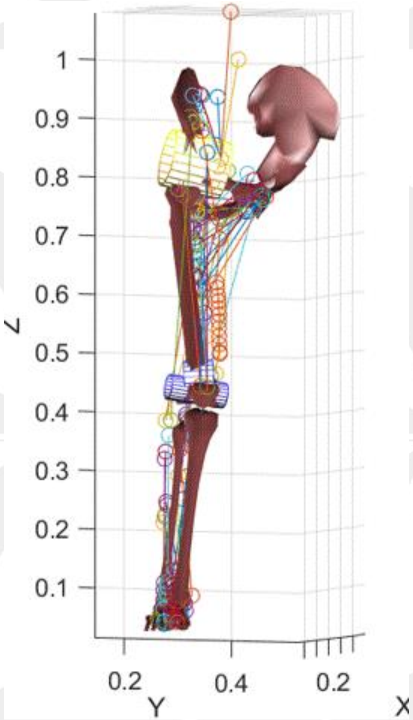
Klein Horsman's (2007) dissection

Hip and knee calibration exercises

Quasistatic model

Programmed in MATLAB and C++

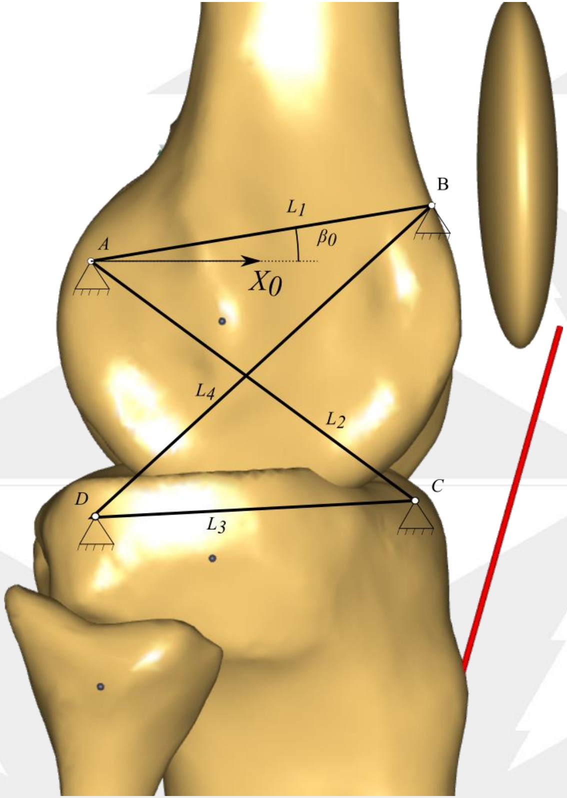




Joint Kinetics

Joints:

- Hip was modeled as a spherical joint.
- Knee was modeled with an articulated quadrilateral
- Ankle was modeled with 2 revolution joints.
- Kinematics chain was modeled with Denavit-Hartenberg.



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Inverse Dynamics

Virtual work: $\vec{Q} = \vec{\tau} + \sum_{i=1}^{n}\left(J_{F_i}^{T}\overrightarrow{F_i}\right)$

Generalized force balance: $\sum_{i=1}^{n_{mus}}\left(J_{F_i}^{T}\overrightarrow{F_i}\right) = -\sum_{j=1}^{n_{ext}}\left(J_{F_j}^{T}\overrightarrow{F_j}\right)$

Muscle lever arms: $J_{F_i}^{T}\overrightarrow{F_i} = J_{F_i}^{T}\overrightarrow{u_i}\cdot F_i = \overrightarrow{C_i}F_i$

Resolution of muscle coactivation

Karush-Kuhn-Tucker Conditions:

Objective function:

$$\min\left(\sum\left(\left(\frac{F_i}{A_i}\right)^2\right)\right)$$

Conditions of equality:

$$\sum_{i=1}^{n_{mus}}\left(\sigma_i \overrightarrow{B_i}\right) = -\overrightarrow{\tau_{ext}}$$

Inequality conditions:

$$\sigma_i \geq 0$$

$$\overrightarrow{B_i} = A_i\overrightarrow{C_i}$$

A direct solution of the Karush-Kuhn-Tucker Conditions has been obtained.

Resolution of muscle coactivation

Function with KKT conditions (example for 2dof):

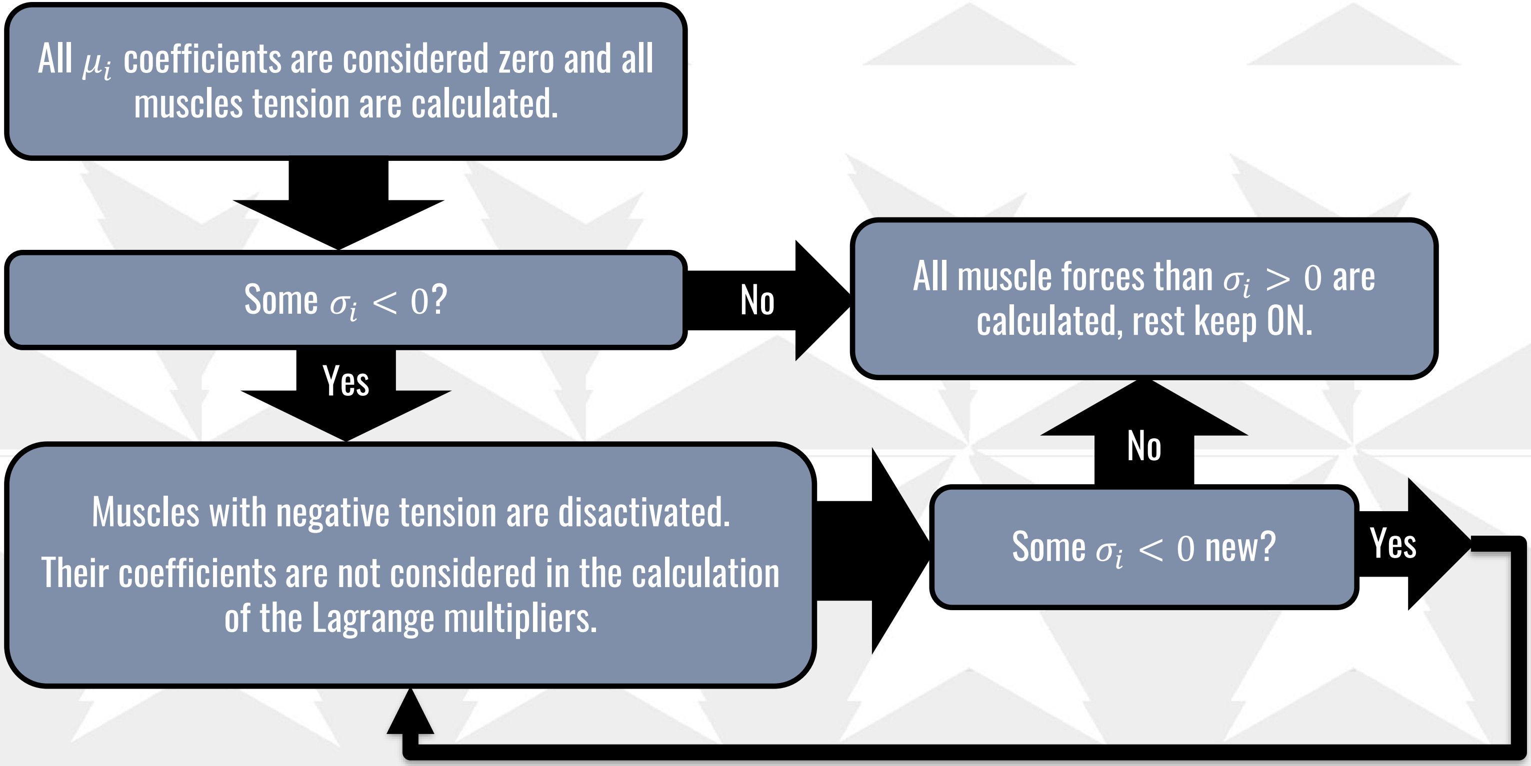
$$F = \sum(\sigma^2) - \lambda_1\left(\sum_{i=1}^{n_{mus}}(\sigma_i B_{i1}) - \tau_1\right) - \lambda_2\left(\sum_{i=1}^{n_{mus}}(\sigma_i B_{i2}) - \tau_2\right) + \sum(\mu_i \sigma_i)$$

Resolution:

$$\sigma_i = \frac{\lambda_1 B_{1i} + \lambda_2 B_{2i}}{2}$$

$$\begin{bmatrix} \frac{\sum\left(B_{1i}^2\right)}{2} & \frac{\sum(B_{1i}B_{2i})}{2} \\ \frac{\sum(B_{1i}B_{2i})}{2} & \frac{\sum\left(B_{1i}^2\right)}{2} \end{bmatrix}^{-1} [\vec{\tau}] = [\vec{\lambda}]$$

Resolution of muscle coactivation



3

Validation process

- Validation difficulties
- Steps for the validation.

Validation difficulties

- An objective validation is not possible in musculoskeletal models.
- Impossible to know the real muscular forces with not invasive techniques.
- Muscle coactivation changes between persons.
- Muscle coactivation depend on the exercises.
- There is not a large amount of empirical data for validation
- Existing empirical data uses old subjects.

Validation process

1. Research question
2. Prototype and verification plan
3. Verification of the model
4. Comparation of the results between “Gold Standard” y empirical data
5. Robustness test
6. Documentation of the model
7. Generate predictions and hypotheses

Is My Model Good Enough? Best Practices for Verification and Validation of Musculoskeletal Models and Simulations of Movement

Hicks (2015)

4

ANYBODY COMPARATION

- Anybody's model used and differences between models.
- Comparation process.
- Experimental data.
- Grand Challenge data.

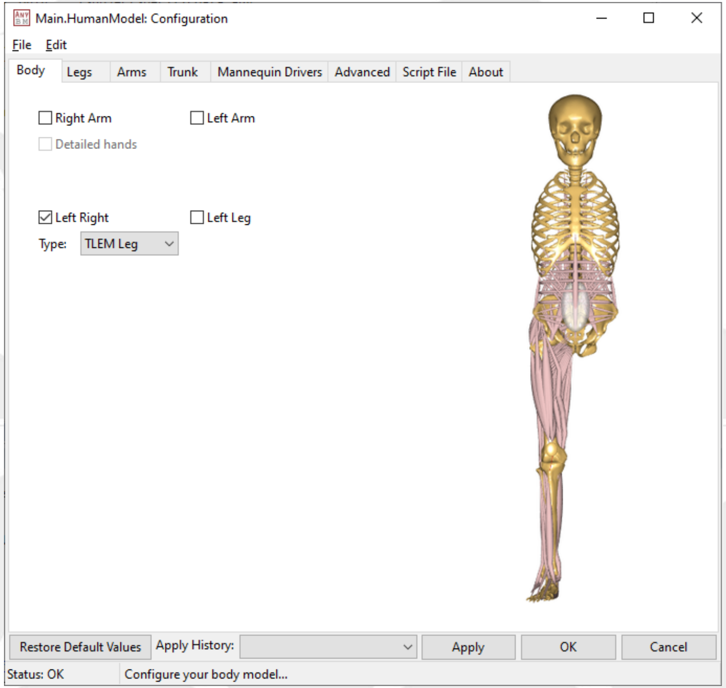
Anybody's model

AnyBody's model configuration:

- The Twente Lower Extremity Model 1.2.
- Hill muscle model disactivated.
- Only the right lower extremity.
- Mobile force sensor.

Differences between models:

- Ankle dissection.
- Knee and Hip.



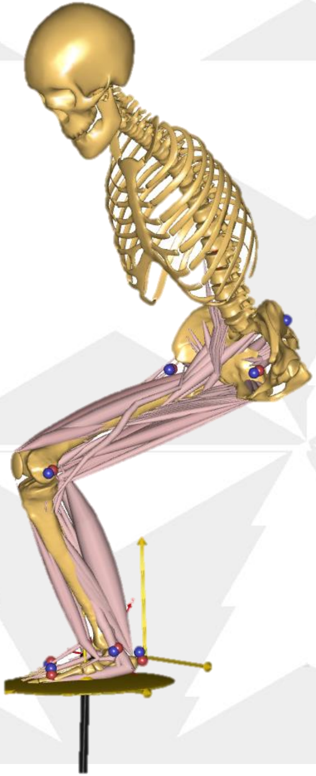
Comparation process

Experimental data:

- Hip, knee and ankle flexion and generalized forces.
- Muscle forces.

Grand Challenge:

- Hip, knee and ankle flexion and generalized forces.
- Muscle forces.
- Electromyography.
- Knee normal contact forces.

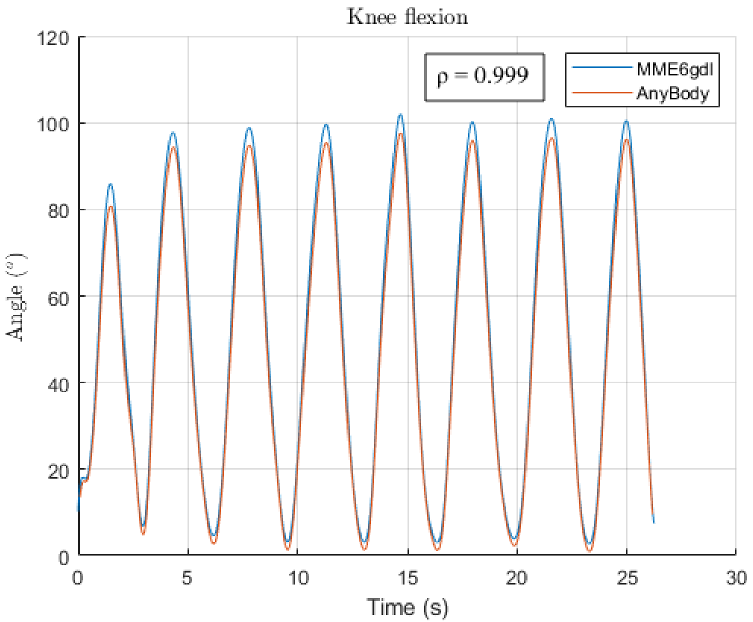


Comparation “Gold Standar”

Joints:

- The joints present comparable results, especially the hip and knee.
- The ankle disagrees due to the difference in data.

	Hip	Knee	Ankle
Flexion angle:	0.906	0.999	0.970
Generalized force:	0.880	0.954	0.680



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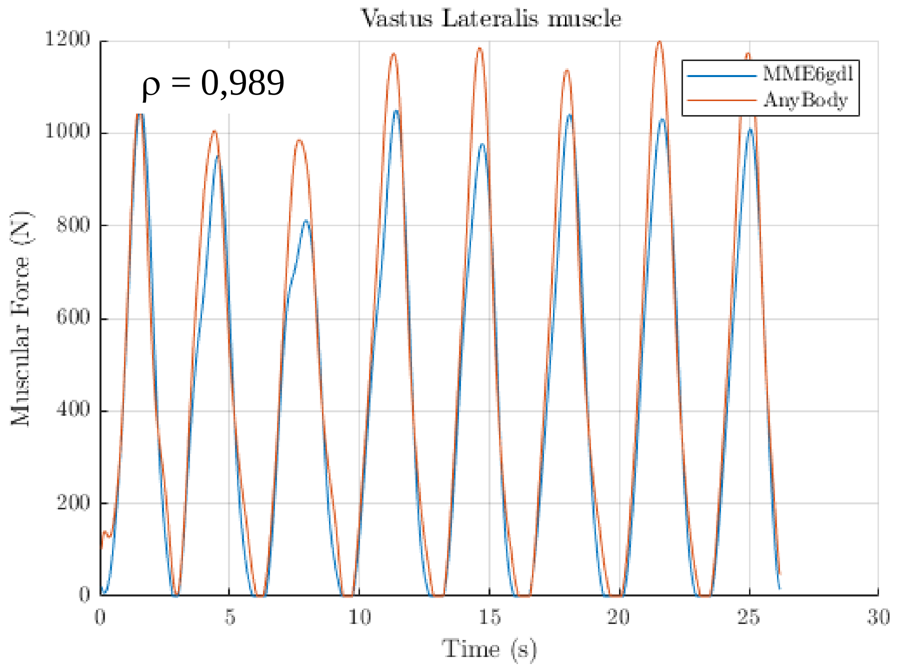
Comparation "Gold Standar"

Comparison conclusions:

- Muscle correlation is high in the most relevant muscles for exercise, the Vastus.

	Vastus medial	Gluteus maximum	Rectus femoris	Iliopsoas Lateral
Correlation :	0.906	0.644	-0.300	0.843

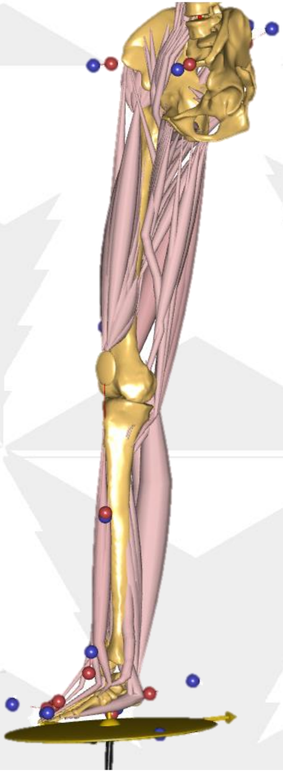
	Gastrocnemius	Sartorius	Semimembranosus
Correlation :	0,868	0,872	0.617



Empirical data comparation

Comparation using "Grand Challenge":

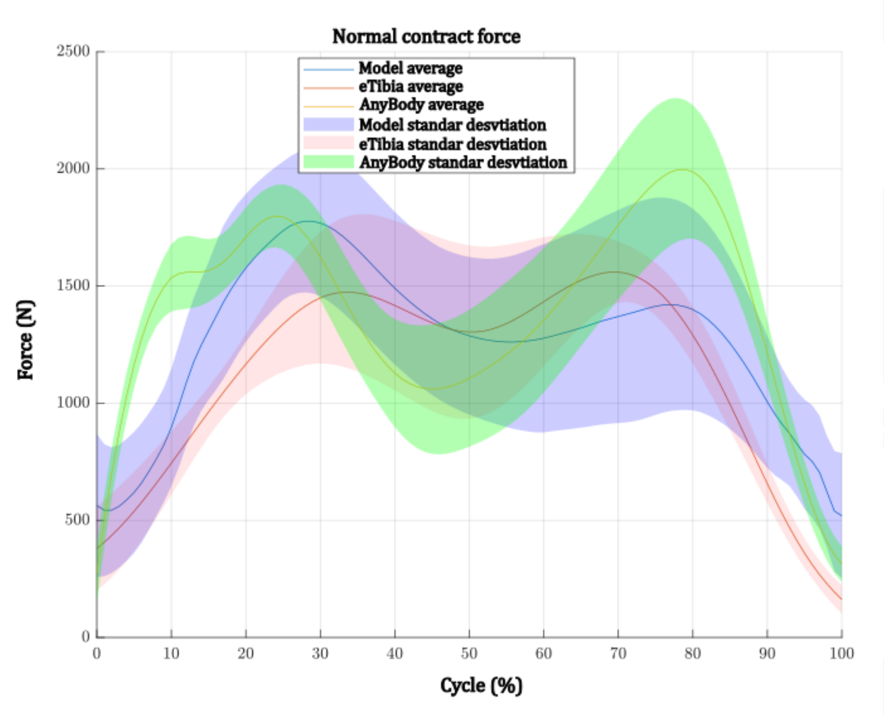
- Sixth Competition "*Grand Challenge Competition to Predict In Vivo Knee Loads*".
- Exercises was simulated in AnyBody and the current model.
- Estimated muscular forces between the two models.
- Estimated knee normal contact between models.



Comparison with empirical data

Conclusions comparison:

- Correlation EMG - RTM : Mean: 0,18.
- Correlation EMG - AnyBody : Mean : 0,18.
- Correlation AnyBody - RTM : Mean : 0,71.
- Correlation eTibia - RTM : Mean : 0,64.
- Correlation eTibia - AnyBody: Mean : 0,46.



5

ROBUSTNESS TEST

- Markers used
- Inertial parameters.

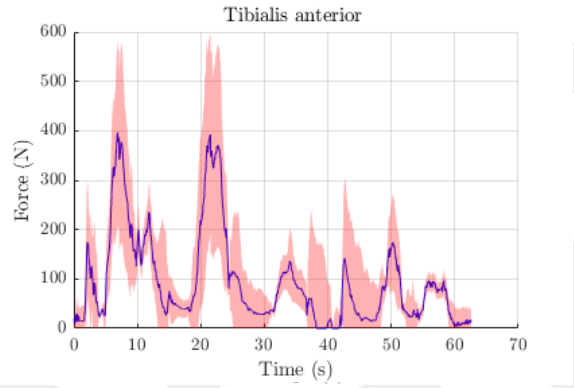
Robustness test

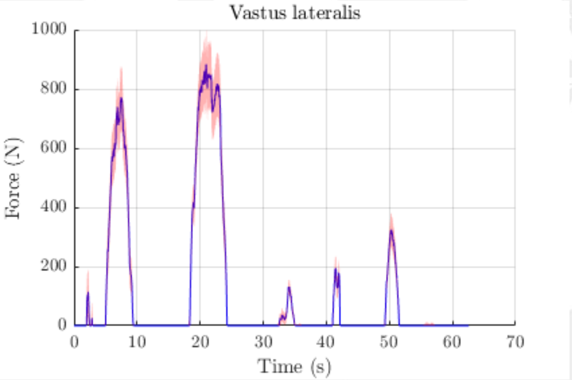
Marker positioning:

- Checking the error in the positioning of the markers, data from Della Croce (1999).
- Knee Flexion/Extension exercises using the robot.

Result:

- Error of approximately 15% in the calculation of muscle forces.
- Error in the Gastrocnemius and Soleus much higher.





Robustness test

Inertial parameters:

- Checking the error in the estimation of the CoM and the mass of the segments.
- Inertial parameters obtained from Dumas (2007).
- Error extracted from the data of McConville (1980) and Young (1983).

Result:

- Error less than 0.1%.

Segment	Man		Woman	
	Masa	CoM	Masa	CoM
Femur	17,1 %	9,9 mm	21,5 %	10,1 mm
Tibia	16,3 %	9,7 mm	20,8 %	6,7 mm
Foot	15,9 %	4,1 mm	14,8 %	3,7 mm

6

TOOLS PROPOSED WITH THE CURRENT MODEL

- Force envelope.
- External equivalent force.

Tools proposed with the current model

Force Envelope:

- Cloud of vectors representing the maximum voluntary contraction (MVC) at final effector of the model.

Equivalent external force:

- External force necessary to achieve the desired muscle activation in a specific muscle.

Force Envelope

- **Objective**: Optimize rehabilitation exercises.
- By knowing the Maximum Voluntary Contraction of a subject, muscular adaptations could be optimized.

Force envelope

Methodology

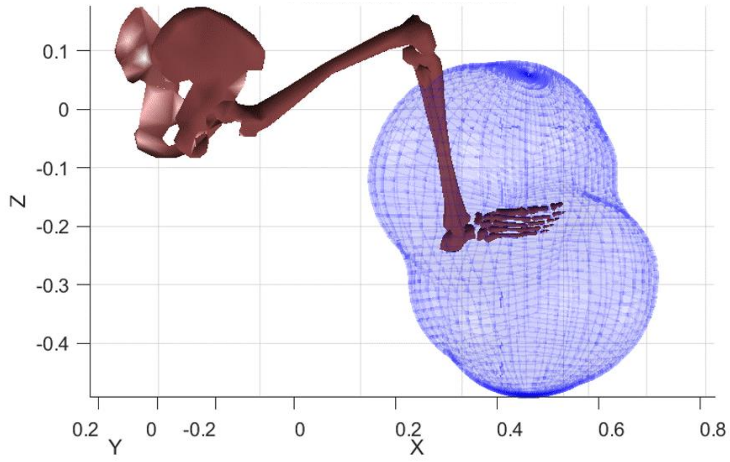
- Muscle forces are projected into equivalent forces in the foot:

$$\begin{bmatrix} \overrightarrow{F_{Pie}} \\ \overrightarrow{M_{Pie}} \end{bmatrix} = J_{Pie}^{-T}\overrightarrow{B_i}\sigma_i$$

- A vector sphere is generated.
- The equivalent forces of each muscle are added.:

$$\begin{bmatrix} \overrightarrow{F_{u_i}} \\ \overrightarrow{M_{u_i}} \end{bmatrix} = \sum\left[\max\left(0, \left(J_{Pie}^{-T}\overrightarrow{B_i}\sigma_i\right)\overrightarrow{u_i}\right) \cdot \overrightarrow{u_i}\right]$$

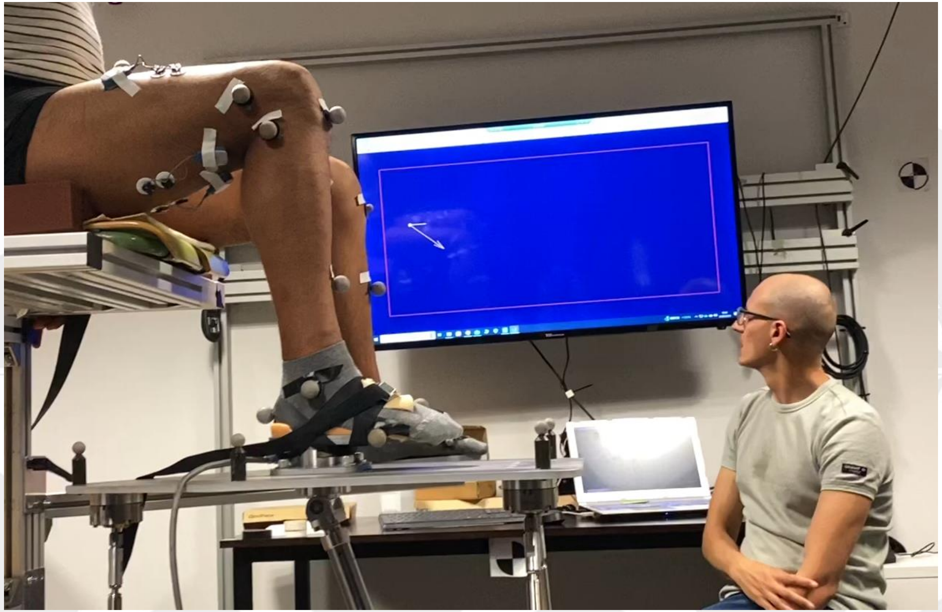
Force envelope



Force envelope

Current experiments:

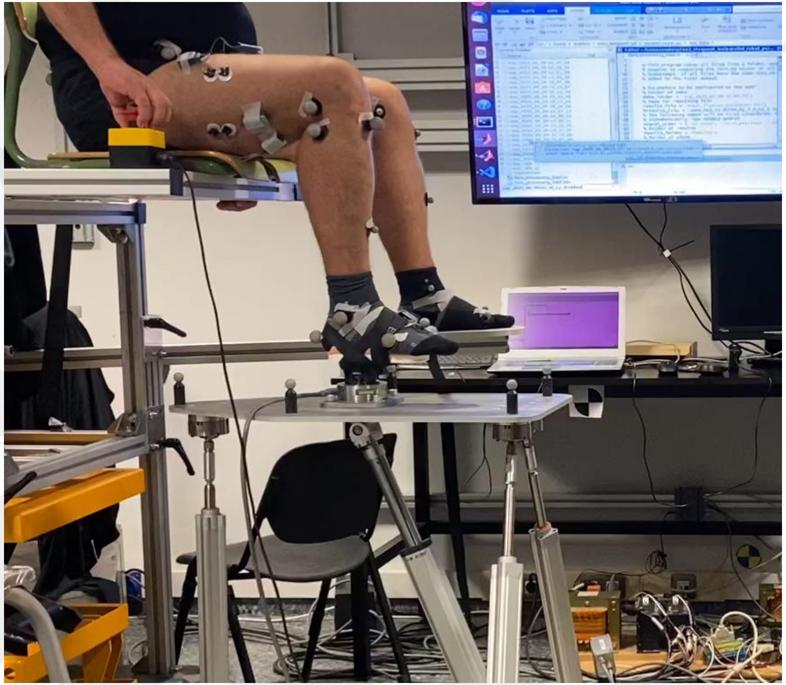
- Calibration of vector circle with MVC.
- Knee extension/flexion with force control.
- Comparison of EMG vs. Envelope estimated activation.



Force envelope

Results:

- Correlation of agonist muscle forces:
  - Hamstring ρ = **0,83**.
  - Quadriceps ρ = **0,79**.



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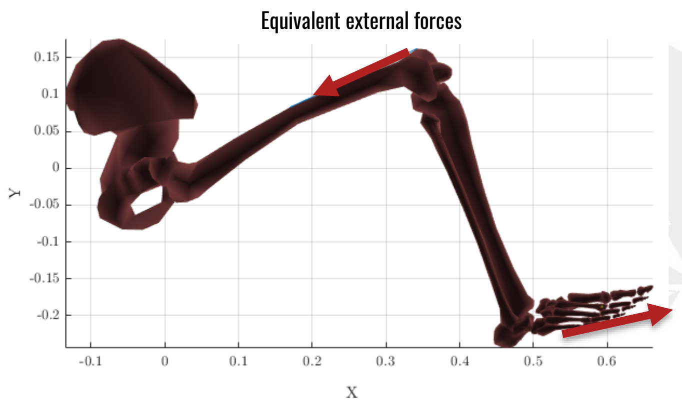
Equivalent external force

- **Objective**: Create trajectories and exercises focused on specifically working the desired muscle.
- Once the direction vector that optimizes the work of the muscle is known, it is possible to optimize the trajectories.

Equivalent external force

Methodology

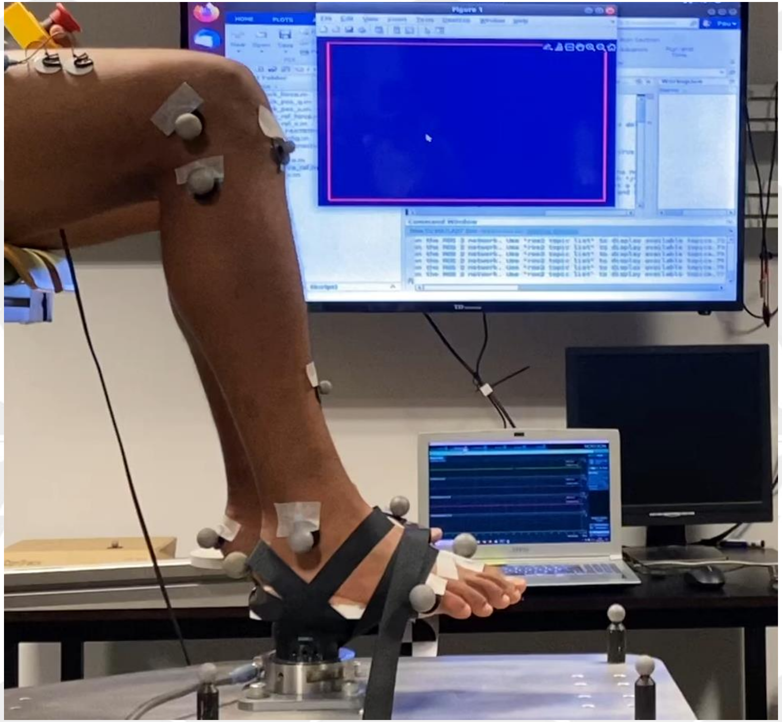
- Calculation of muscle tension: $\sigma_i = \frac{\sum_j \lambda_j B_{ji}}{2}$
- For 1 DOF muscles, the equation is determined: $\lambda_j = \frac{2\sigma_i}{B_{ij}}$
- The dynamics are solved: $\vec{\tau} = A^* \vec{\lambda}$
- Generalized forces are projected: $\begin{bmatrix} \overrightarrow{F_{Foot}} \\ \overrightarrow{M_{Foot}} \end{bmatrix} = J_{Pie}^{-T} \vec{\tau}$



Equivalent external force

Current experiments:

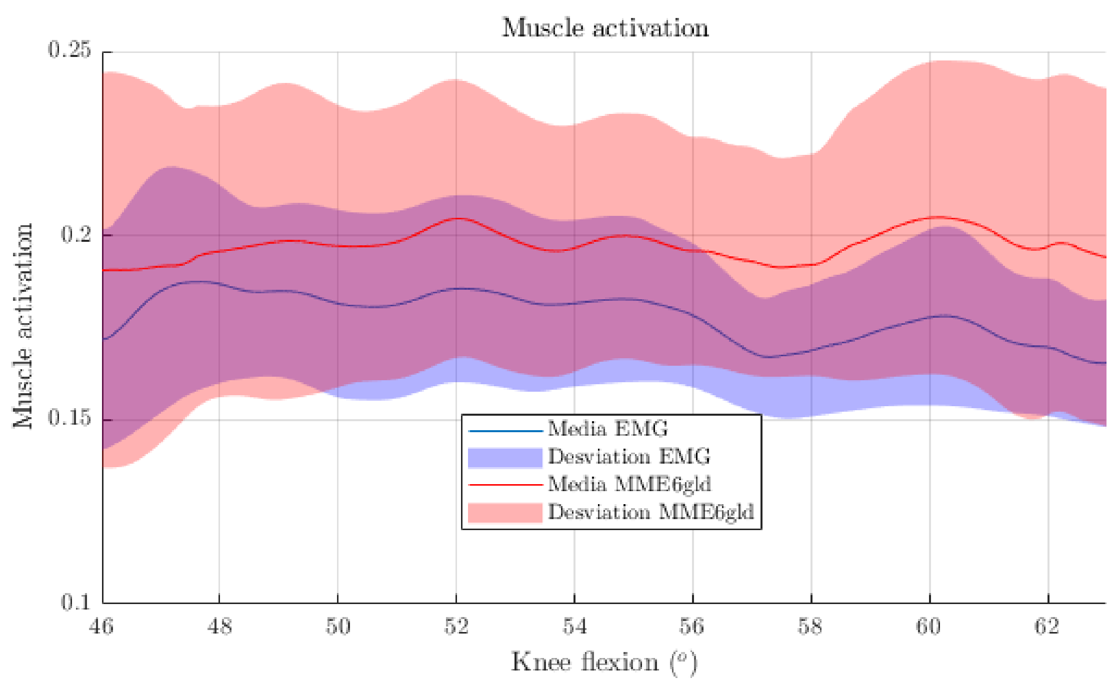
- Calculation of the equivalent force in a knee extension.
- Vastus Lateralis reference muscle.
- Comparison between EMG – estimated force.



Equivalent external force

Results:

- Relative force tracking error: 10,35%.
- Relative muscle activation error: 10,87%.



7

CONCLUSIONS AND FUTURE RESEARCH

Conclusions

1

Real-time Musculoskeletal Model

A six-degree-of-freedom musculoskeletal model capable of real-time calculation of muscular and joint forces has been developed

2

Experimental validation of the Model

The developed model has been validated and verified for its concurrent use with the rehabilitation robot.

3

Development of new tools for rehabilitation

Two rehabilitation tools have been developed using the ME model: the force envelope and the equivalent external force.

Future research

1

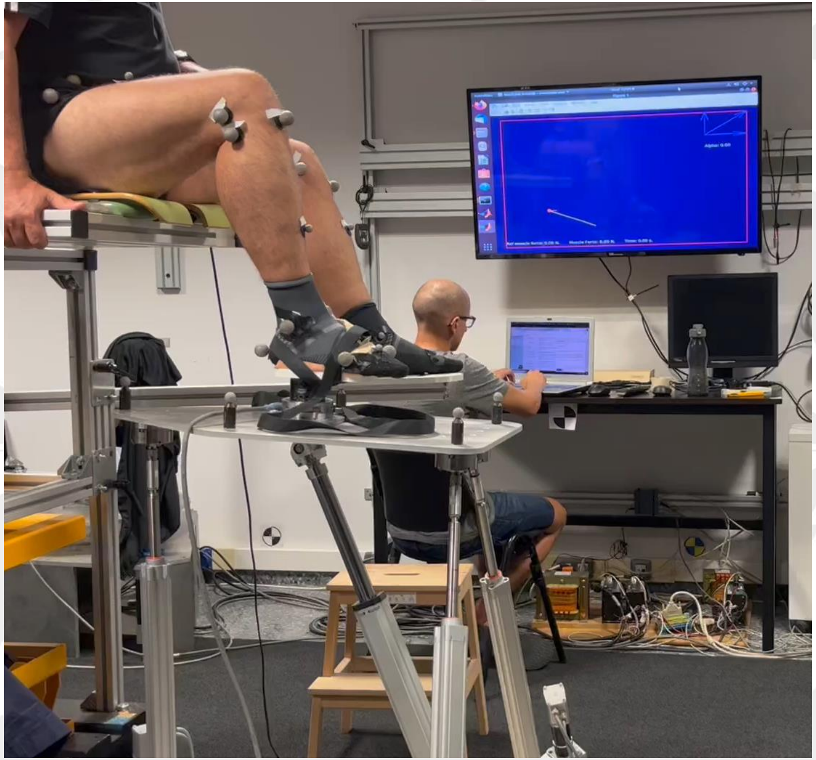
Rehabilitation Exercises with Patients

The new rehabilitations tools will be applied in the rehabilitation process of real patients where the new tools could optimize the rehabilitation process, improve the patient recovery and reduce the clinic time.

2

Application of the Model in advanced rehabilitation robots

The musculoskeletal model will be applied in new advanced rehabilitation control system of the rehabilitation parallel robot. Using the model to generate recovery trajectories and adapt exercises at the maximum voluntary contraction of the patients.



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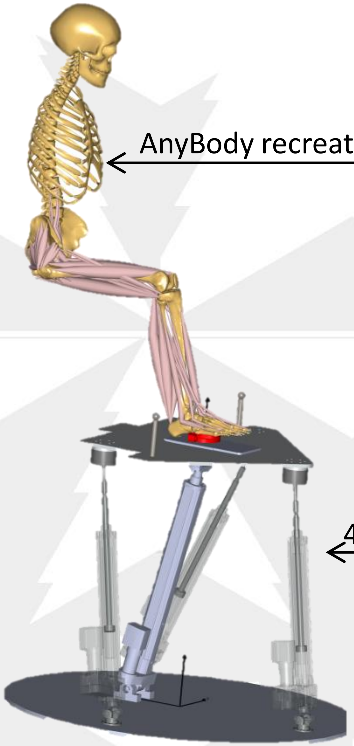
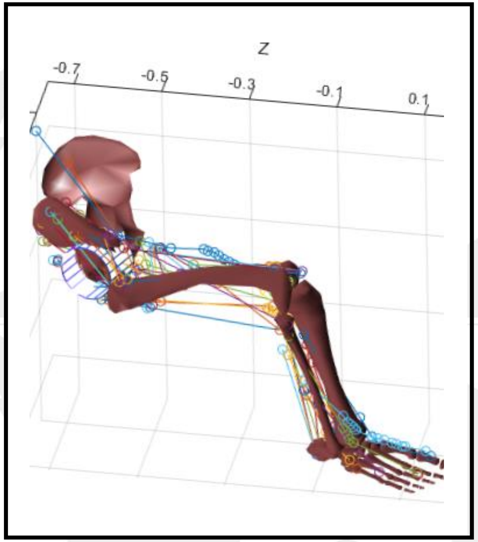


AnyBody recreation of the exercises

Real-time Musculoskeletal model

4 dof knee rehabilitation robot



Autor: **Pau Zamora Ortiz**

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Resources

- **www.anybodytech.com**
  - Events, Webcast library, Publication list, …
- **www.anyscript.org**
  - Wiki, Blog, Repositories, Forum
- **Events**
  - **Feb 2 – 6**: Orthopaedic Research Society – Annual meeting 2024
  - **Feb 15**: AnyBody Summit 2024
  - **Mar 12**: [Webcast] An analysis of hip joint contact forces in people with femoroacetabular impingement syndrome during squat tasks
    - Mattia Perrone, Research Scientist at Rush University Medical Center.

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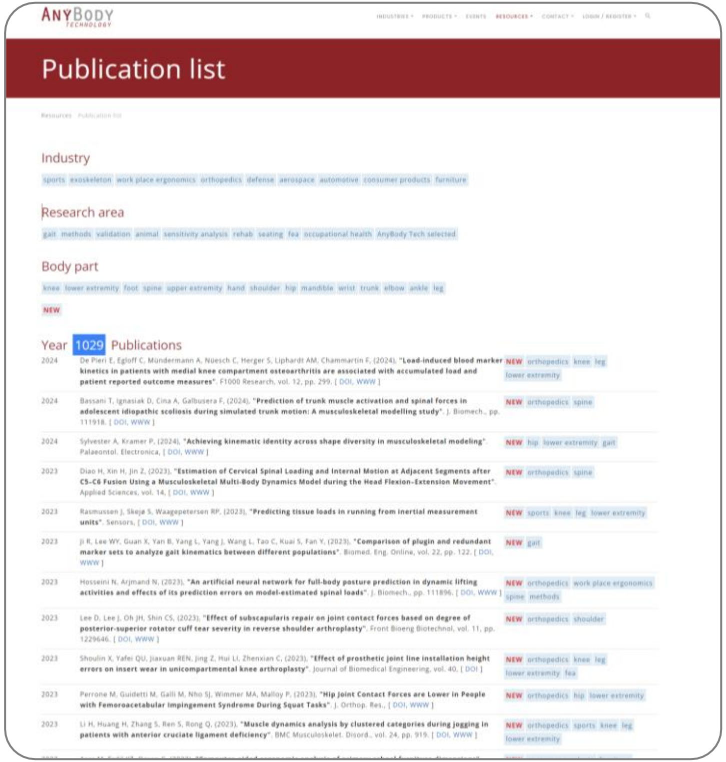

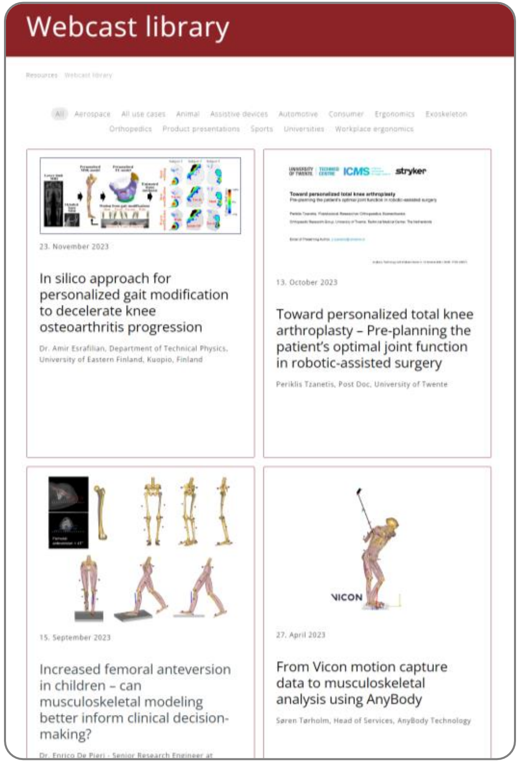

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