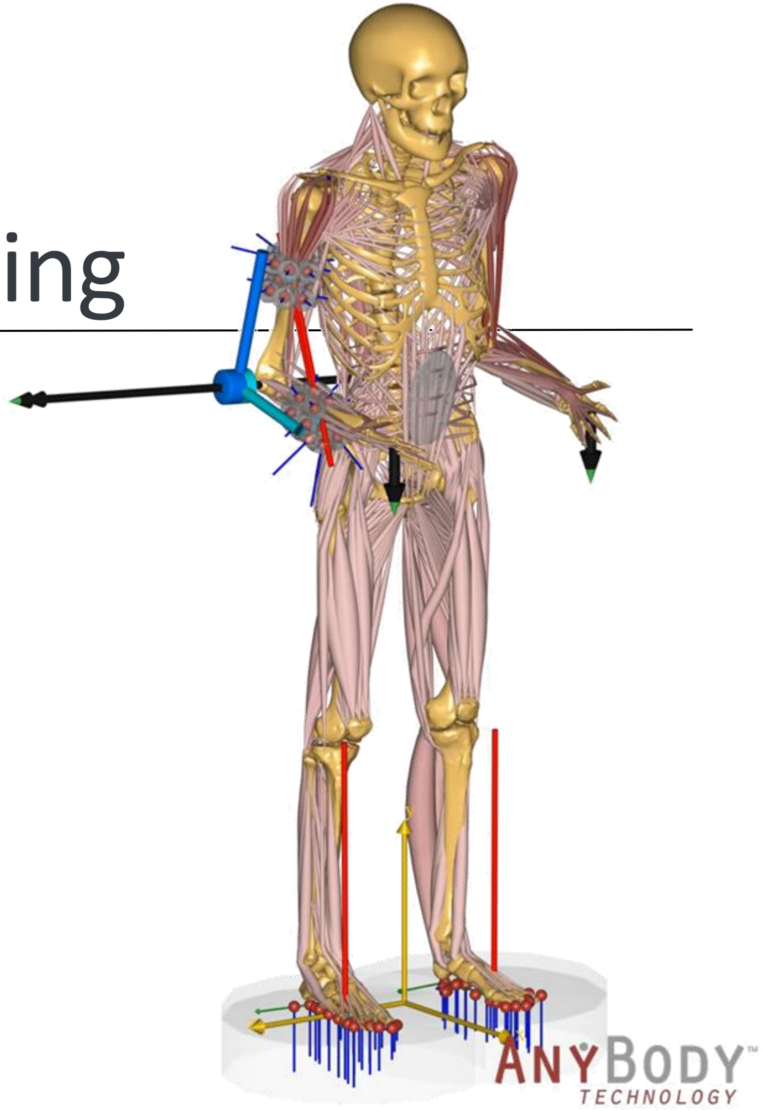
The webcast will begin shortly…

An introduction to exoskeleton design using musculoskeletal modeling

September 26th , 2022



Outline

- Introduction to the AnyBody Modeling System
- Presentation by Divyaksh S. Chander
- Upcoming events
- Question and answer session

Presenter:
Divyaksh S. Chander, Ph.D
Biomechanical Specialist

AnyBody Technology
Denmark

Host:
Kristoffer Iversen
Technical Sales Executive

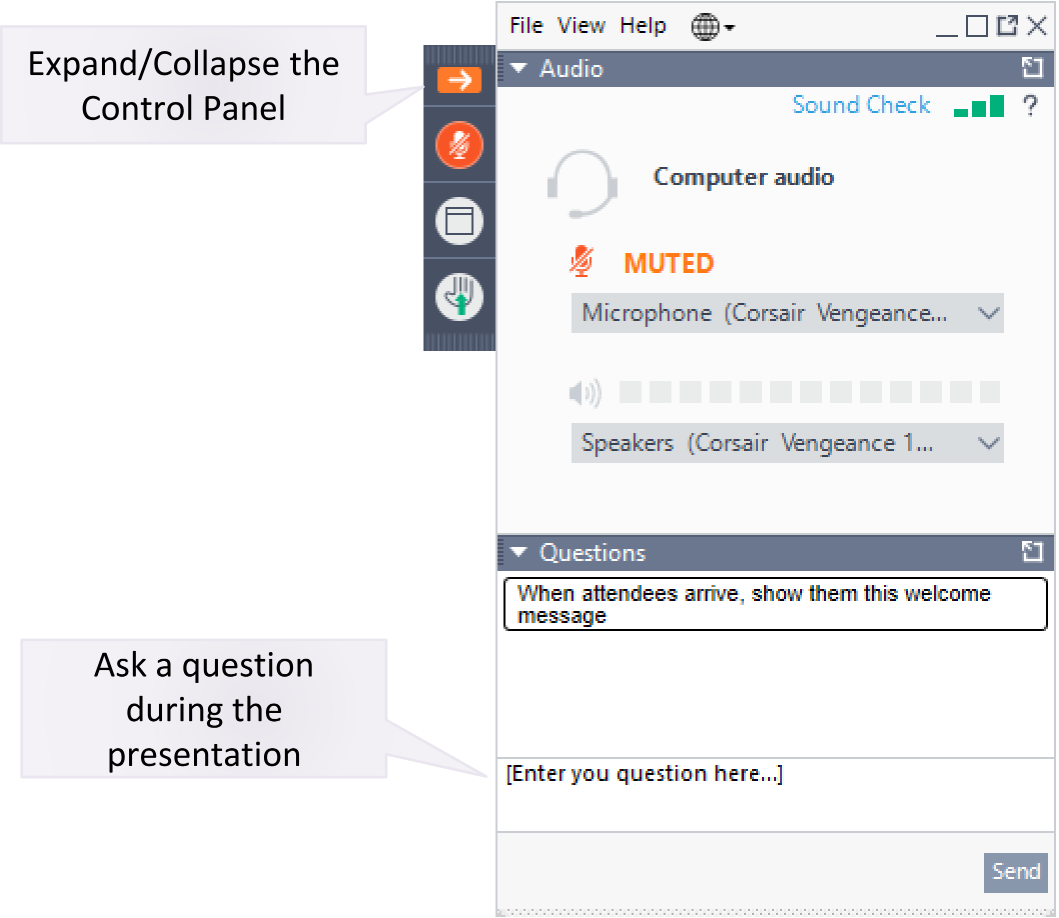
AnyBody Technology
Denmark

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.



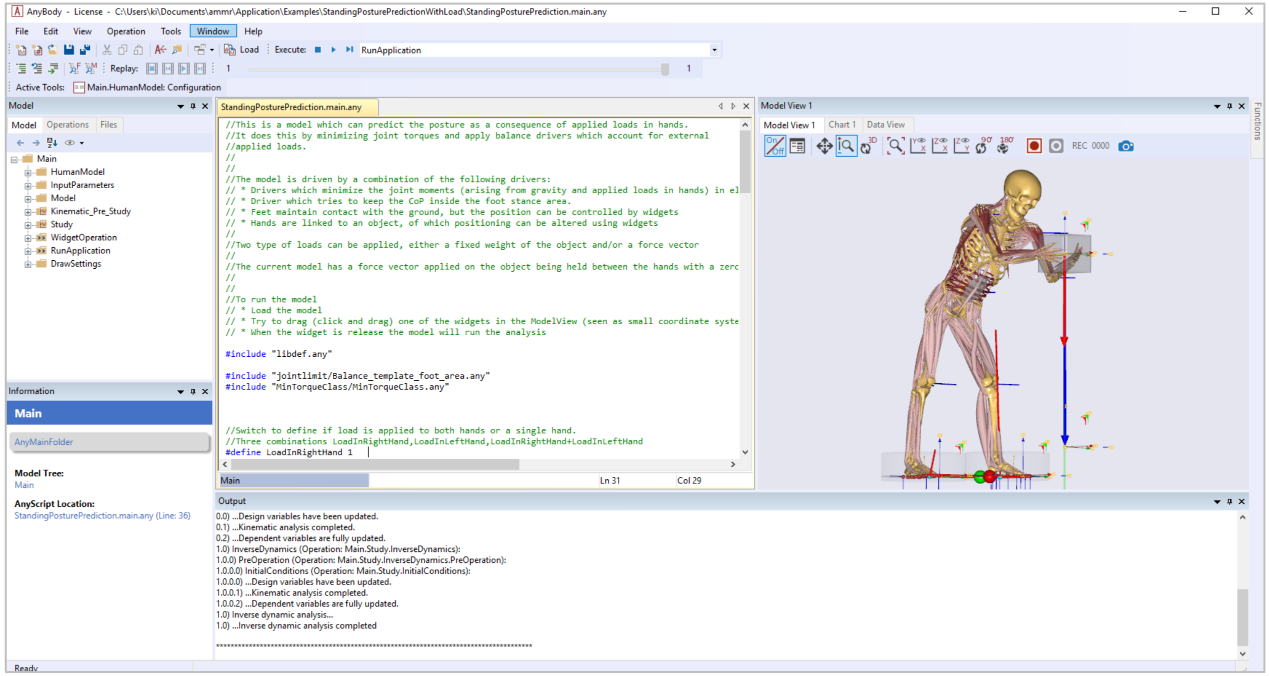
Musculoskeletal Simulation

Motion Data
Kinematics and Forces

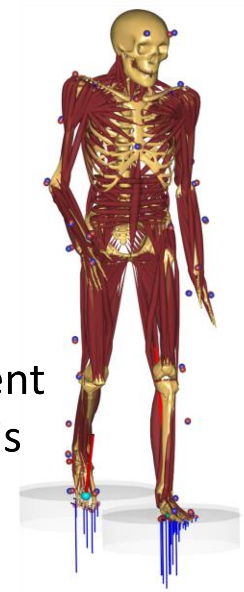
ANYBODY
Modeling System

Body Loads

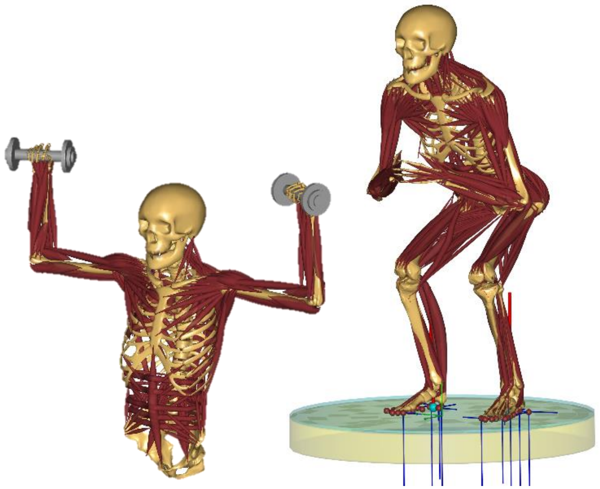
- Joint moments
- Muscle forces
- Joint reaction forces



Product optimization design

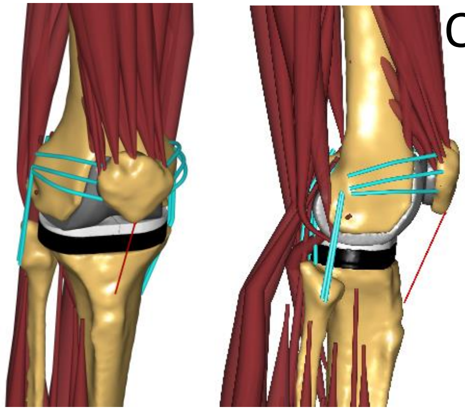


Movement Analysis

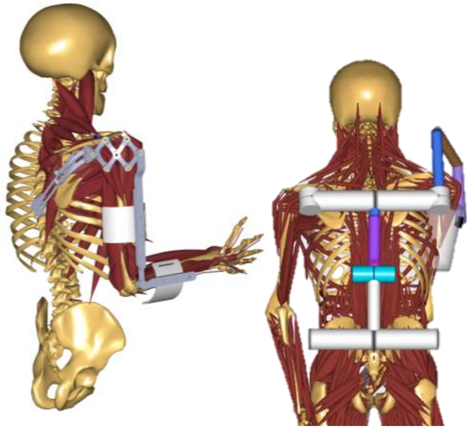


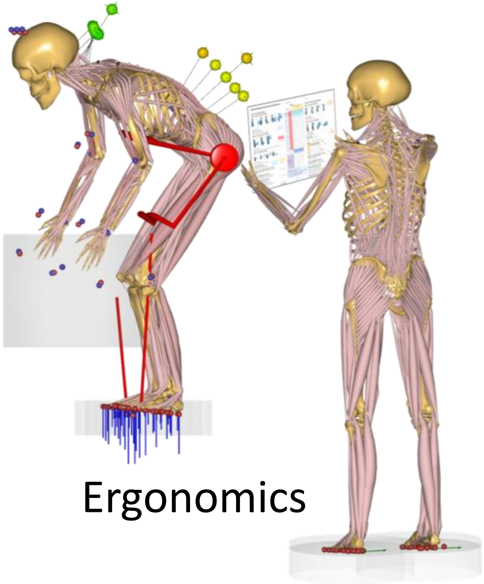
Sports

ANYBODY Modeling System



Orthopedics and rehab





Ergonomics

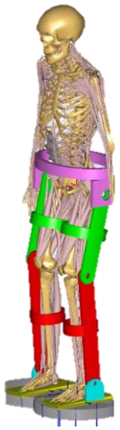
Assistive Devices

AnyBody Modeling System

Motion and Forces

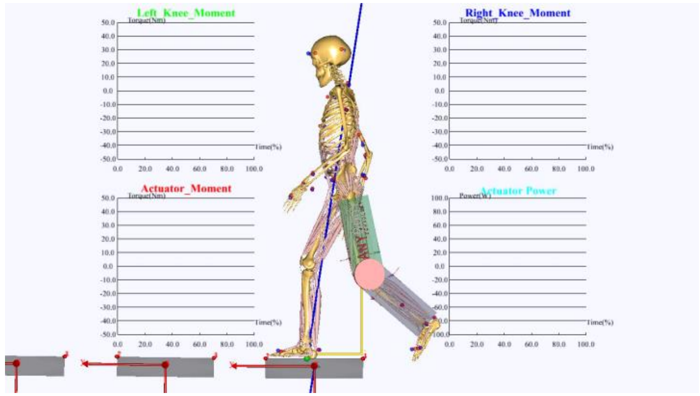
Body model

Environment model



Inverse dynamics
Muscle recruitment

Simulation



Internal body loads
- Muscle forces
- Joint moments

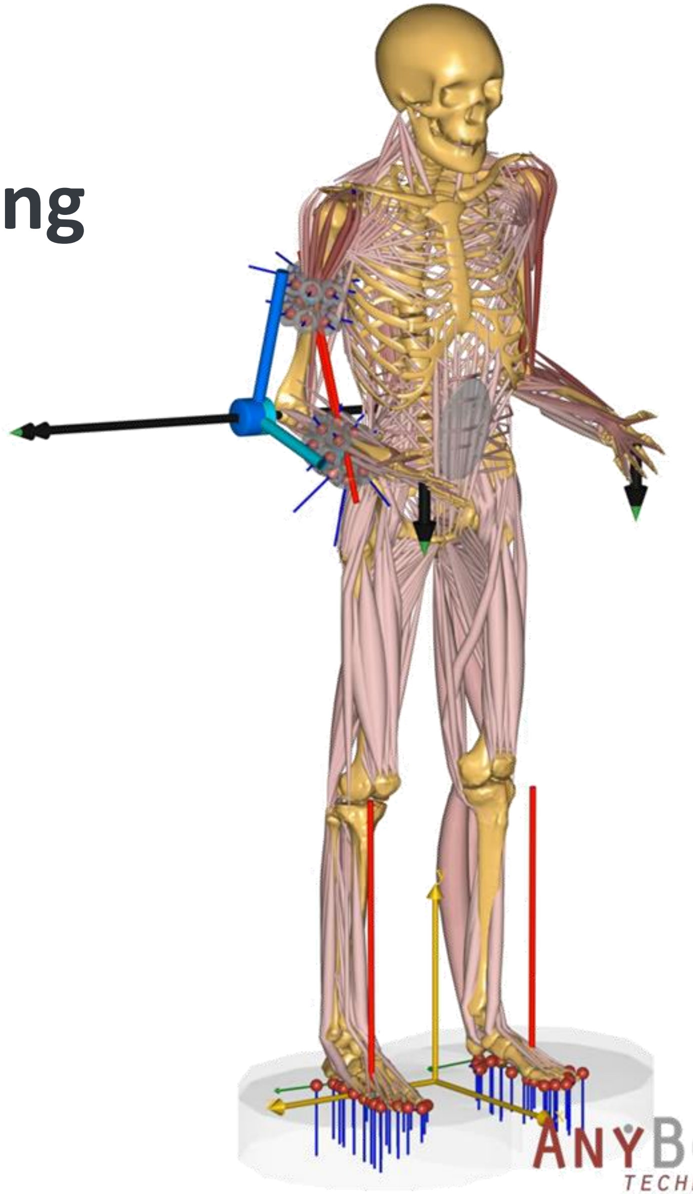
Design Optimization

Post Processing (e.g., Finite element tools)

An introduction to exoskeleton design using musculoskeletal modeling

Presented by Biomechanical specialist

Divyaksh S. Chander



An introduction to exoskeleton design using musculoskeletal modelling

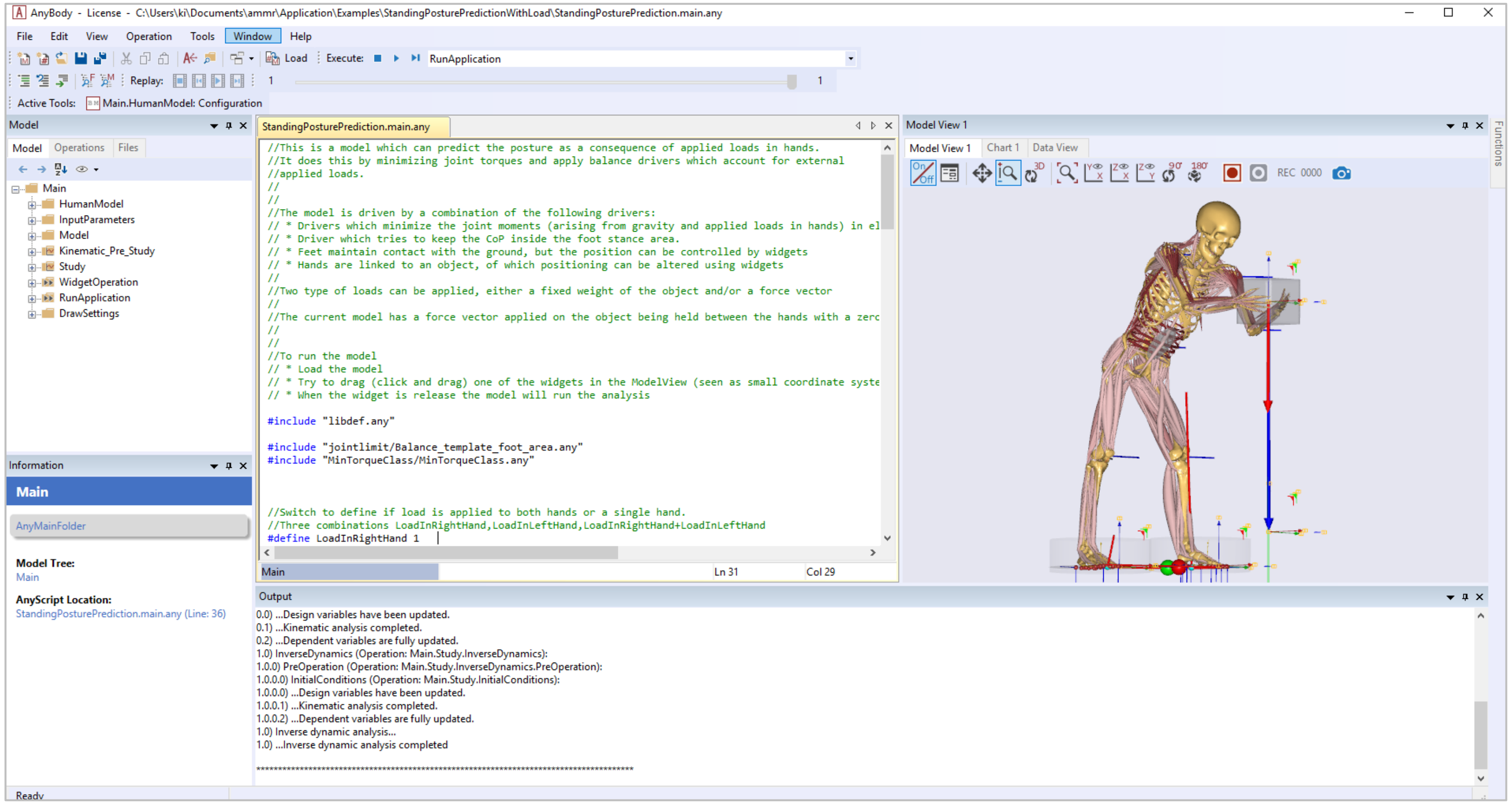
ANYBODY TECHNOLOGY

Outline

- Introduction to AnyBody Modeling System
- Application of musculoskeletal models in exoskeleton design
  - Examples of human-exoskeleton co-simulation
- Modelling of human-exoskeleton connection
  - Kinematics and kinetics
- Conclusion
- Question and answer

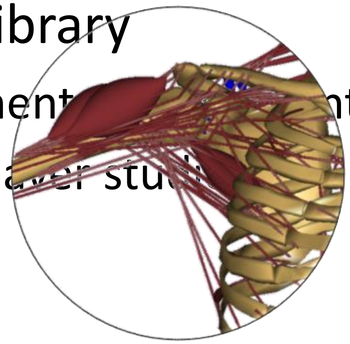
AnyBody Modeling System

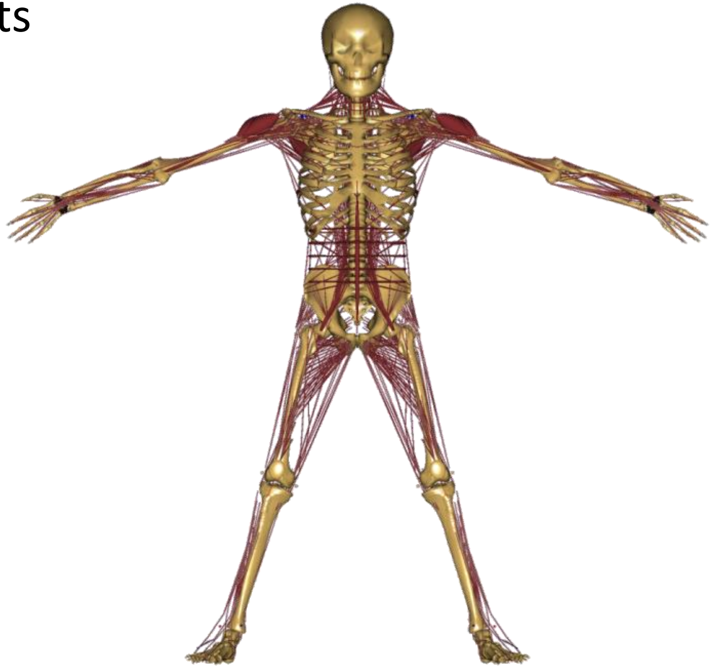
- Musculoskeletal analysis
  - Muscle forces
  - Joint forces and moments
  - Activation patterns
  - Metabolic energy
- Open-Body models (AMMR)
- Customize your model
  - Motion capture
  - Imaging → Patient-specific anatomy
  - CAD → Accurate motion environment
- And do more with outputs!
  - Access every internal variable
  - Export to FE software
  - Office systems

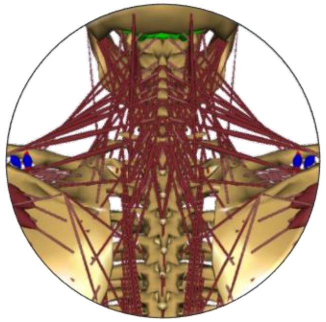


The AnyBody Managed Model Repository™

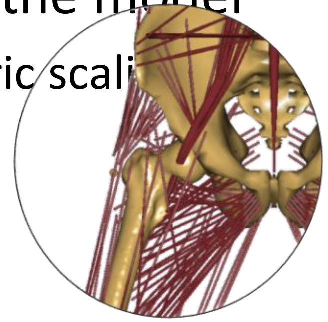
- Open model library
  - Muscles, ligament… …nts
  - Detailed – Cad… stu…
  - Validated
  - Published

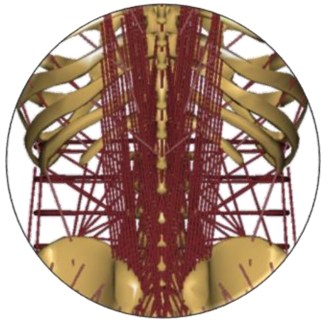






- Personalizing the model
  - Anthropometric scali…
  - Morphing





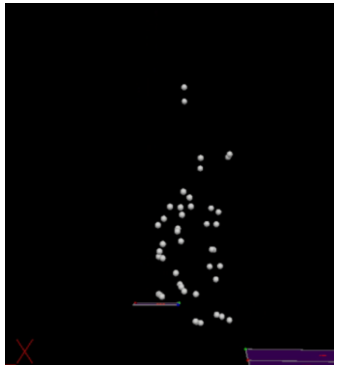
Workflow

MS Model

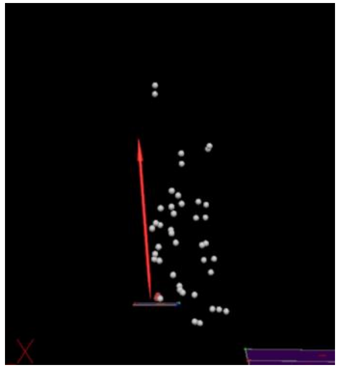
Motion Analysis to estimate internal body loads

Kinematics analysis → Inverse dynamics

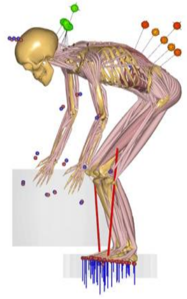
Measured or Predicted



Motion data



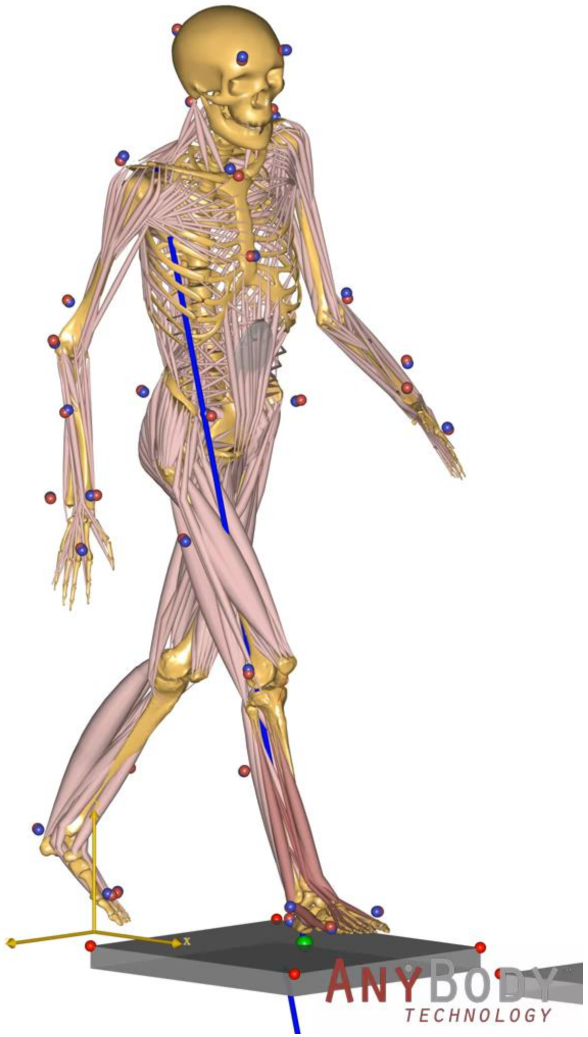
External Forces



Body joint torques
Joint reaction forces
Muscle activation
...

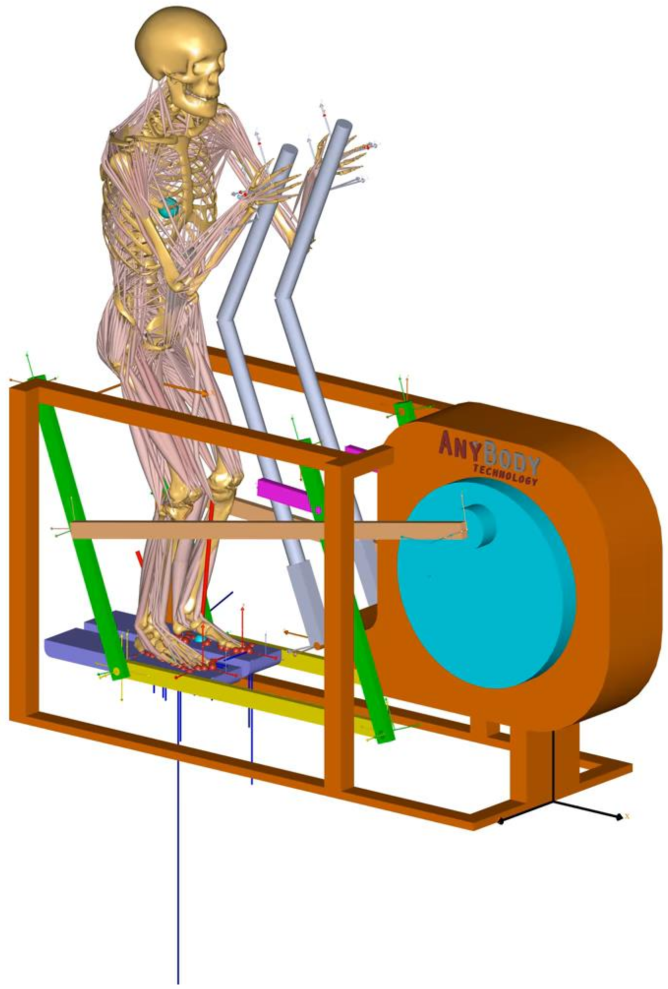
Motion

- Free motion
  - Standard MoCap (C3D files)
  - BVH files (joint angles)
- Environment driven
  - Man-machine interface
- Predicted motion
  - Posture optimization
- Force-dependent motion
  - Internal joint displacement



Forces

- Inertia forces
- Environment forces (boundary conditions)
  - Measured forces
  - Interface forces between human and environment model
  - Analytical/synthetic forces
- Internal body forces (output)
  - Muscles forces
  - Joint forces



Kinematics Formulation

- Full Cartesian Formulation
  - Position and orientation of each segment (6 DOF): three positions and three rotations
  - Constraints: Joints or drivers

- Determinate system

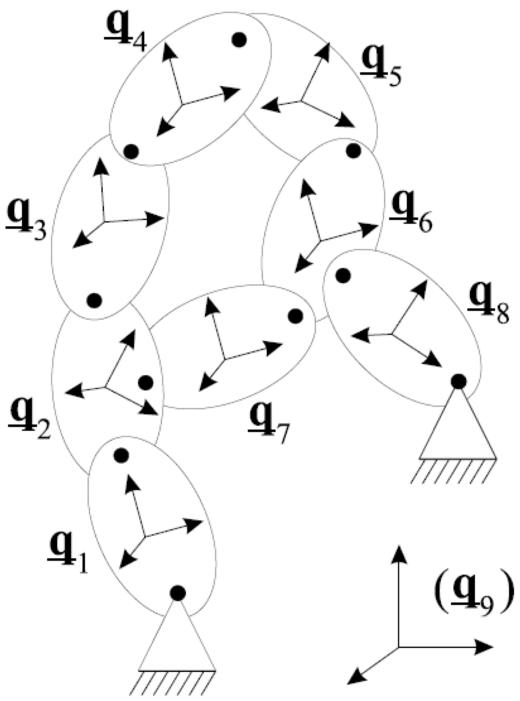
$$\underline{\Phi}(\underline{q}(t),t)=0$$

- Over-Determinate system
  - Hard and soft constraints
  - Optimization problem

$$\min_{\underline{q}(t)} G(\underline{\Psi}(\underline{q}(t),t))$$

$$s.t.\ \ \underline{\Phi}(\underline{q}(t),t)=\underline{0}$$

$$G=\sum_{i=1}^{Nsoft} W_i \times \underline{\Psi}_i^{\,2}$$

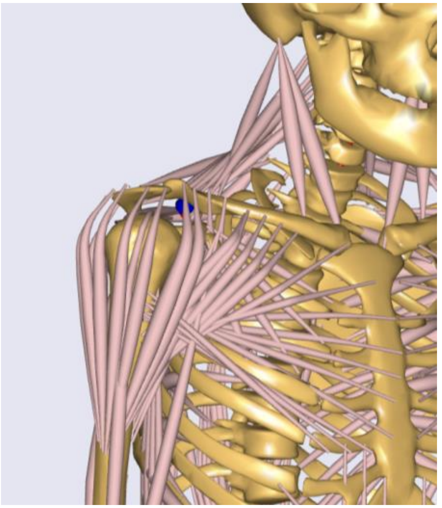


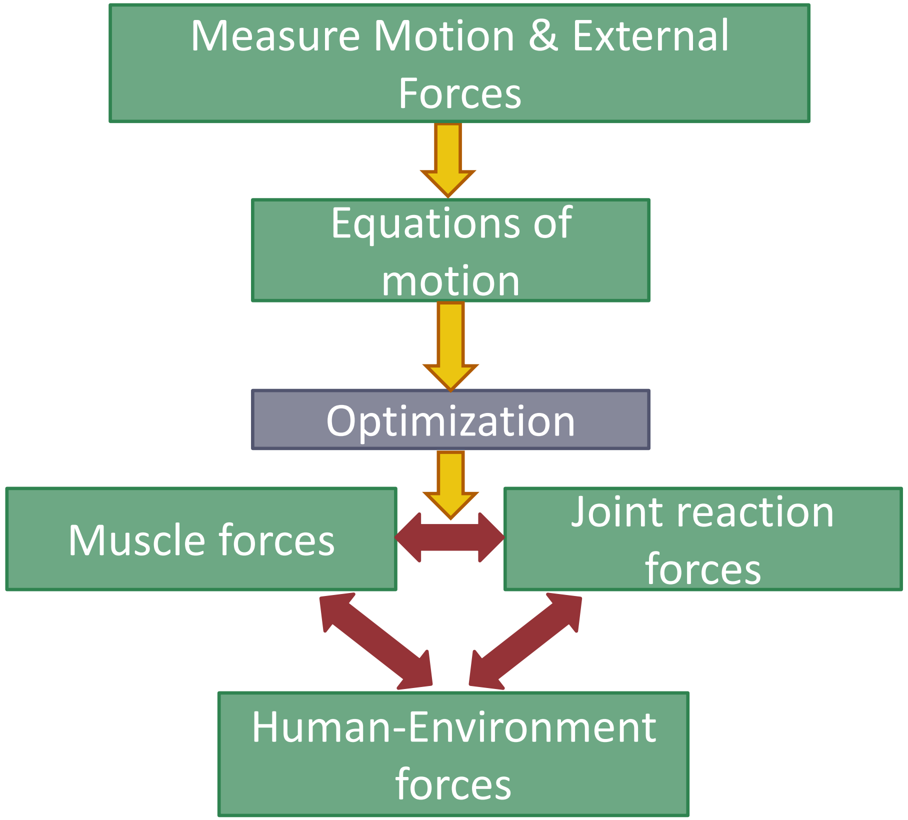
M. Damsgaard et al. (2006): Analysis of musculoskeletal systems in the AnyBody Modeling System. Simulation Modelling Practice and Theory 14.8: 1100-1111. DOI: 10.1016/j.simpat.2006.09.001

M.S. Andersen et al. (2009): Kinematic analysis of over-determinate biomechanical systems. Computer methods in biomechanics and biomedical engineering 12.4: 371-384. DOI: 10.1080/10255840802459412

Inverse Dynamics Formulation

- Direct Muscle Recruitment
- Handles Closed Loop





Objective function. Different choices give different muscle recruitment patterns.

Dynamic equilibrium equations

Minimize

$$G(\mathbf{f}^{(\mathbf{M})})$$

Subject to

$$\mathbf{Cf} = \mathbf{d}$$

$$f_i^{(M)} \geq 0, \quad i \in \{1,..,n^{(M)}\}$$

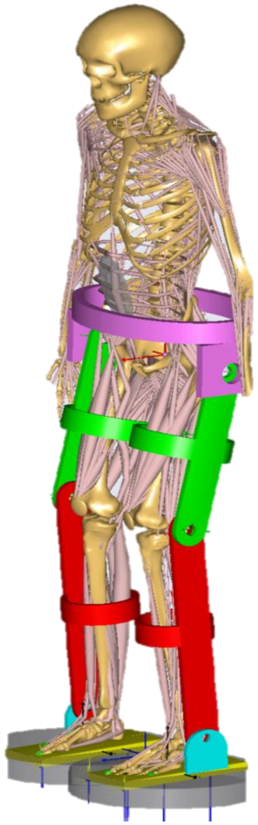
M. Damsgaard et al. (2006): Analysis of musculoskeletal systems in the AnyBody Modeling System. Simulation Modelling Practice and Theory 14.8: 1100-1111. DOI: 10.1016/j.simpat.2006.09.001

MS models in design of assistive devices

Design Questions

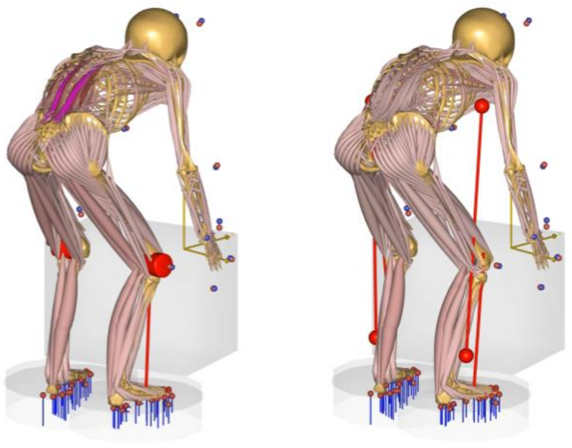
- Starting from a conceptual design of an exoskeleton you may have these questions:
  - What are the affected human variables?
  - How will the load be redistributed?
  - How will it change metabolic energy?
  - How much power do my actuators need to have?
  - How to attach an exoskeleton to the human?
  - How to document the effect of the exoskeleton?

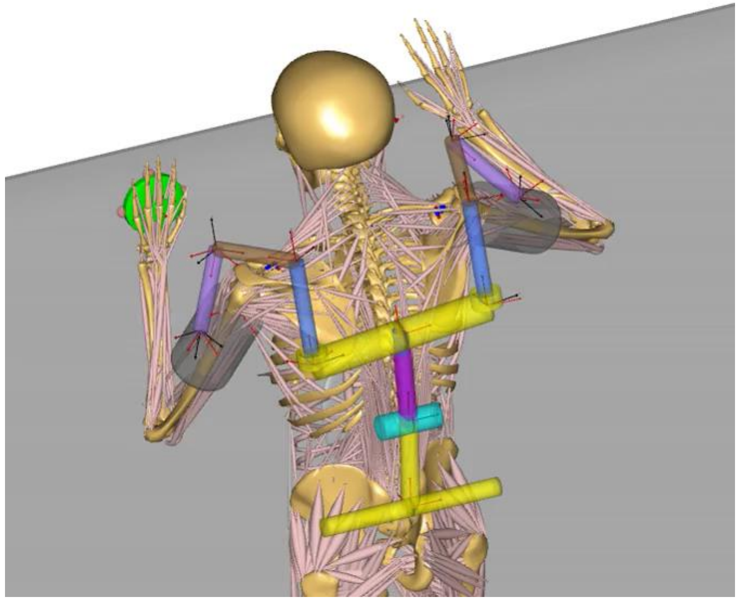
- Combined Human-Exoskeleton simulation helps answers question like these

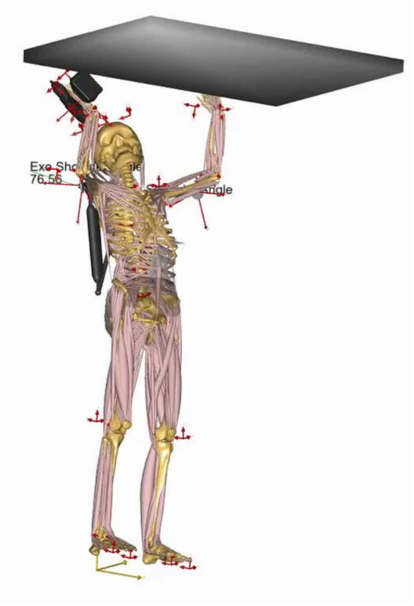


Application of MS models in Exo Design

Conceptual Stage → Virtual Prototyping → Physical Evaluation

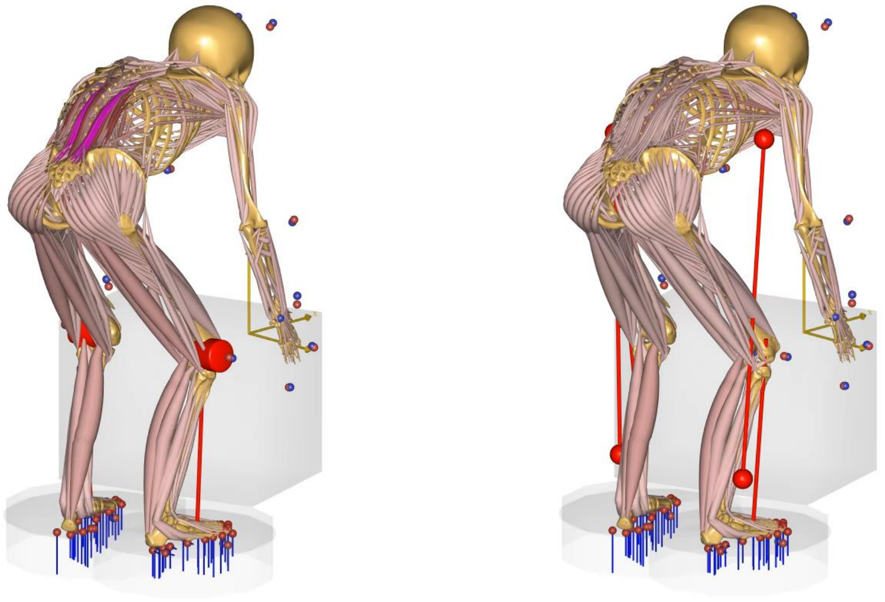






Conceptual Stage

- Baseline
  - Current Situation
  - Reference load
- Assisted Joint
  - Ideal assistance directly to joints
- Exoskeleton Concept
  - Active, passive, etc.
  - Linear or rotational
- Assistive Torque
  - Peak and average power requirement

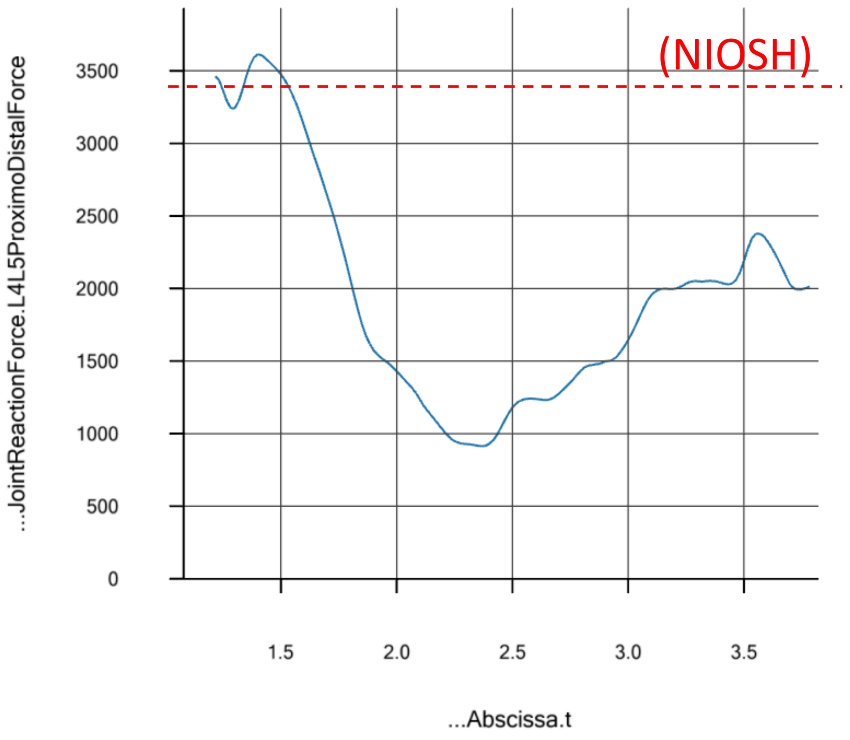


Conceptual Exoskeleton

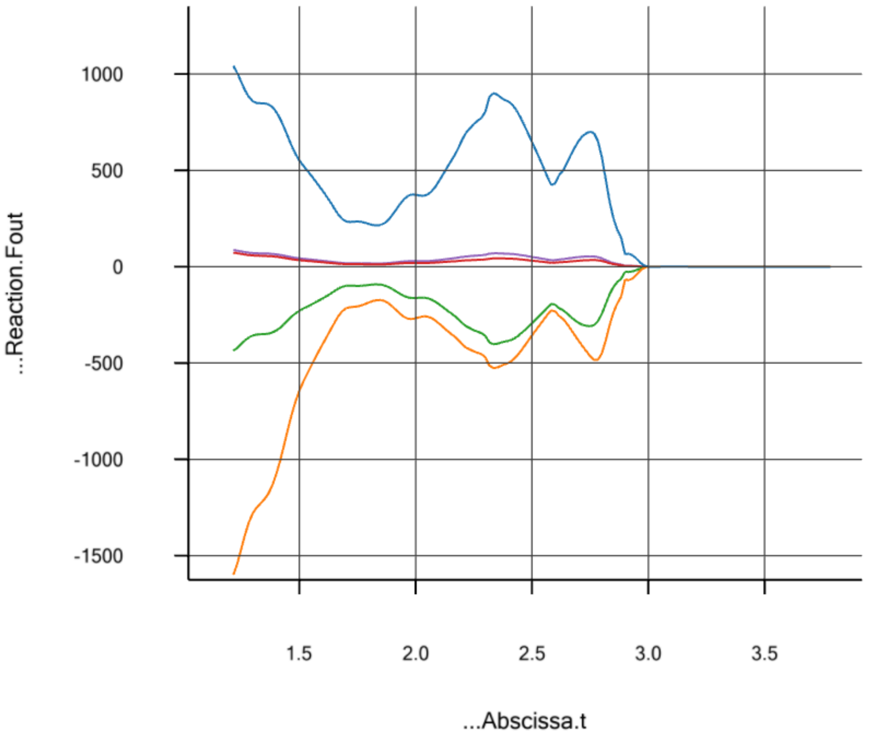
- Task Analysis
  - Establish baseline and target

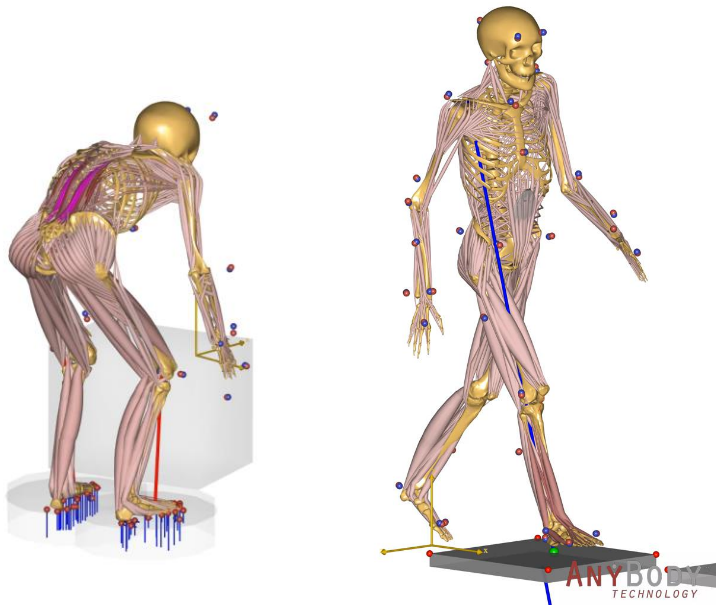
"Simulation-Driven Conceptual Design of Exoskeletons." Webcast by Prof. John Rasmussen, Aalborg University 29 March 2022. https://www.anybodytech.com/simulation-driven-conceptual-design-of-exoskeletons/
Model available in AMMR v 2.4.0 and later

L4-L5 Compression Force (N)



Patella-Femur Reaction Force (N)



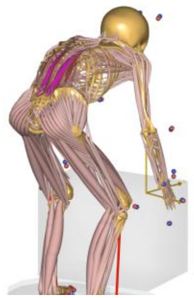
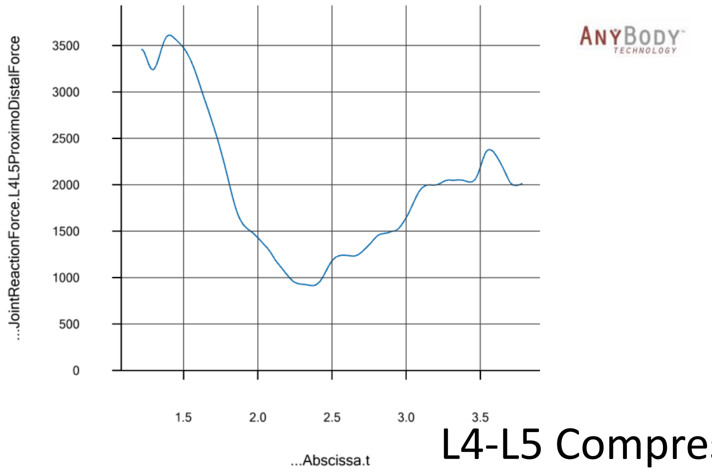


Conceptual Exoskeleton

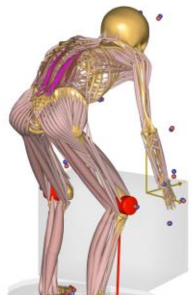
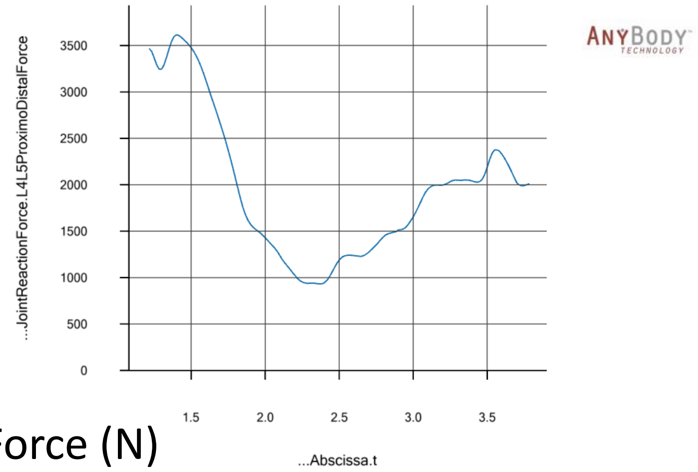
- Study different concepts
  - Idealized Assistance. NO DETAILED CAD MODEL

"Simulation-Driven Conceptual Design of Exoskeletons." Webcast by Prof. John Rasmussen, Aalborg University
29 March 2022. https://www.anybodytech.com/simulation-driven-conceptual-design-of-exoskeletons/
Model available in AMMR v 2.4.0 and later

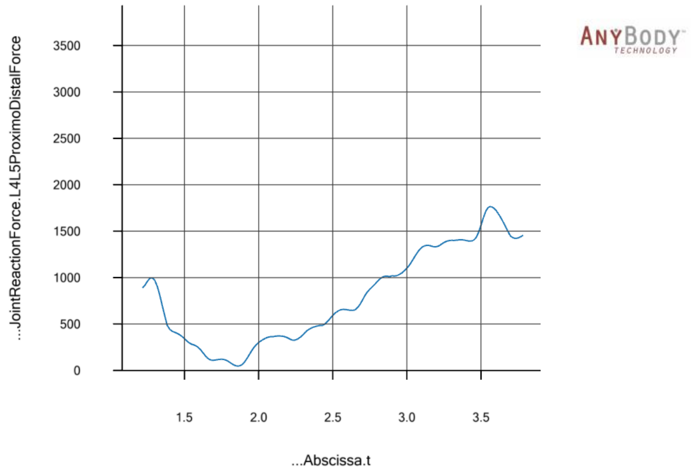
No Assistance

Rotational Springs

Linear Springs

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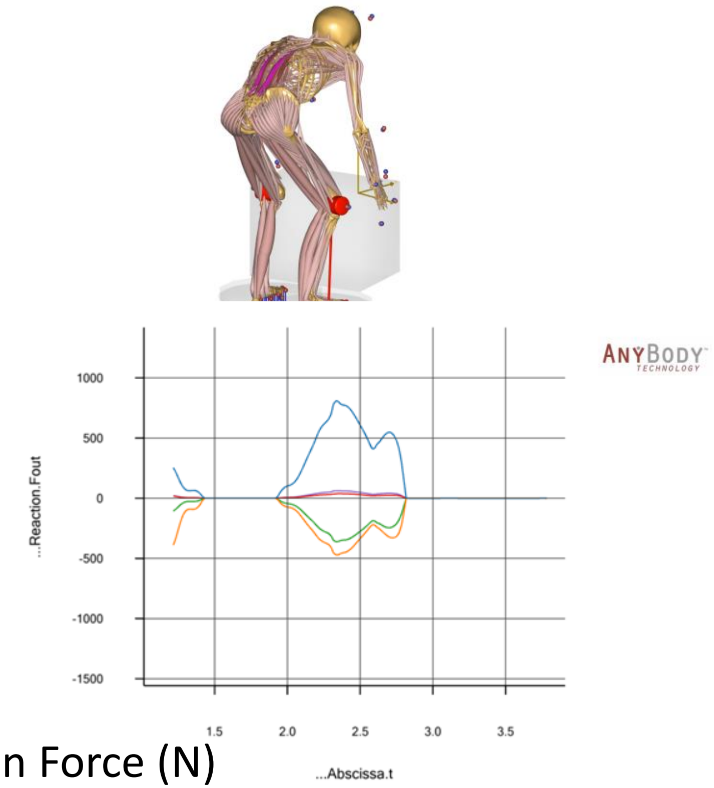
No Assistance

Rotational Springs



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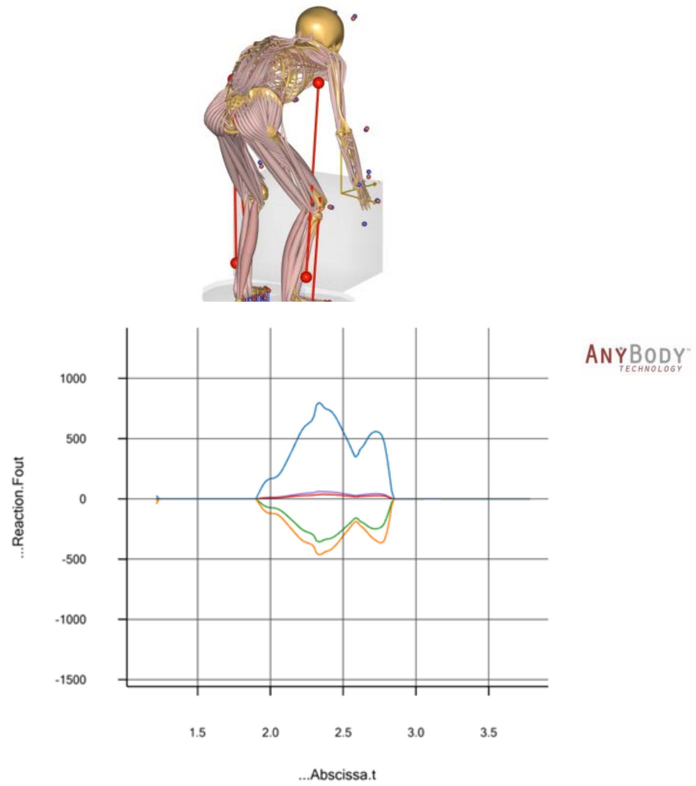
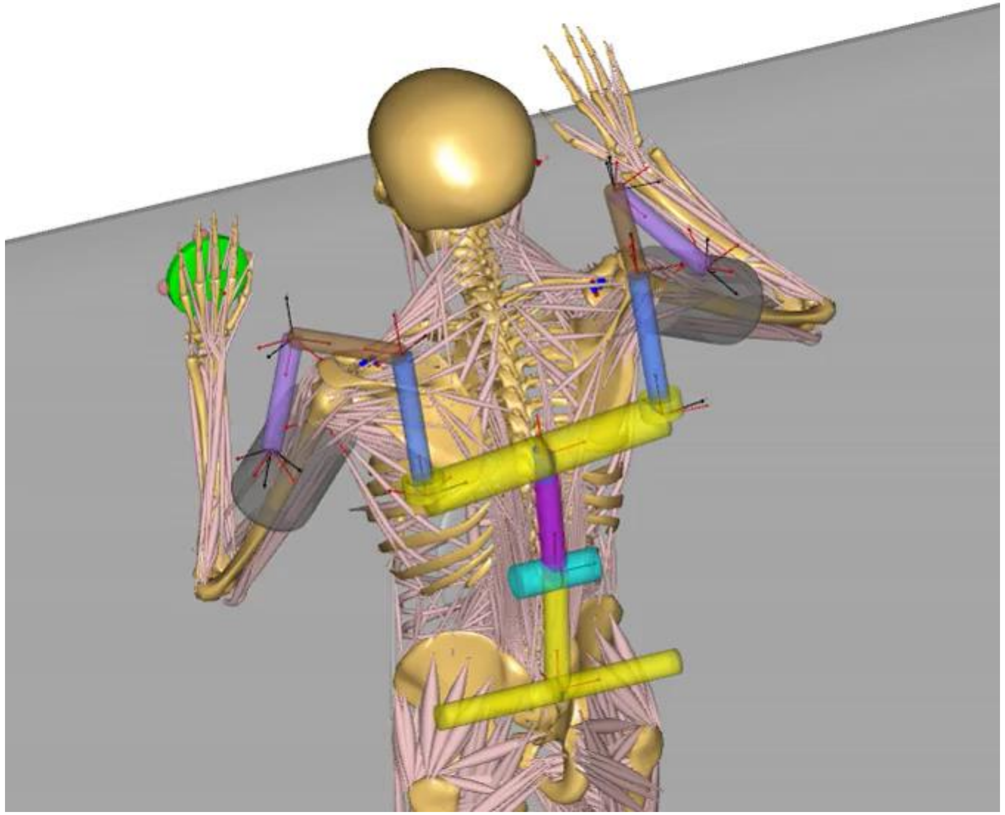


Patella-Femur Reaction Force (N)

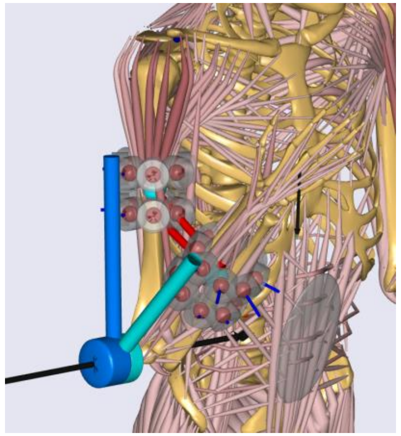
Virtual Prototyping Stage

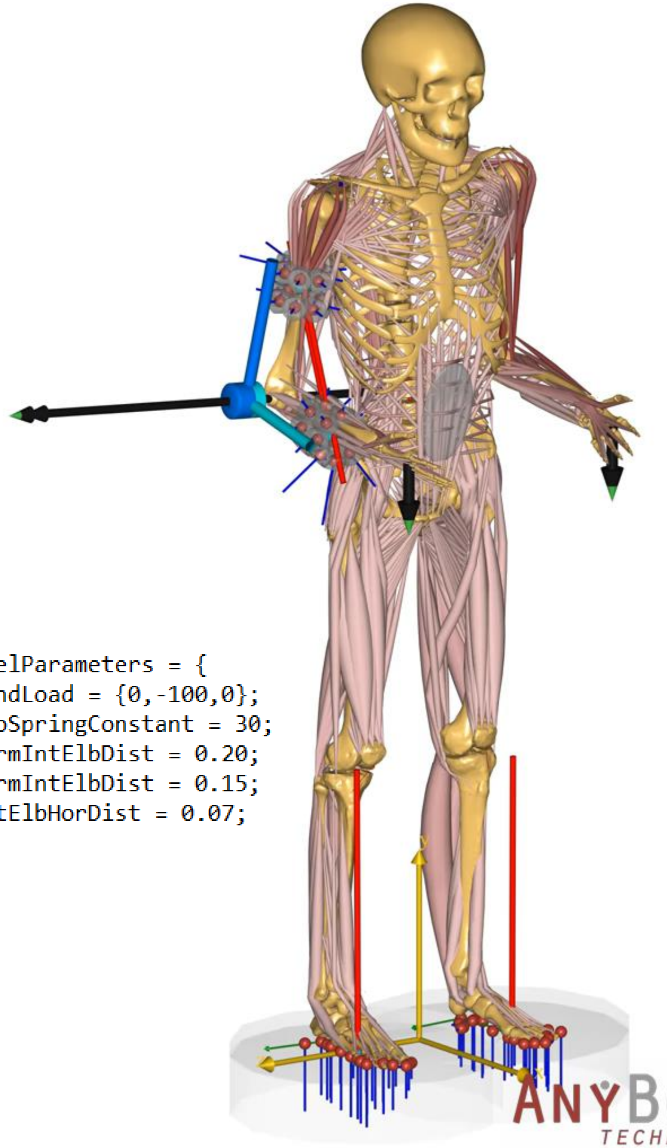
- CAD model
  - Mass and inertia properties
  - Detailed mechanism
- Exo geometry
  - Kinematic alignment
  - Attachment points
- Interface shape
  - Area of contact
  - Shape
- Assitive Torque



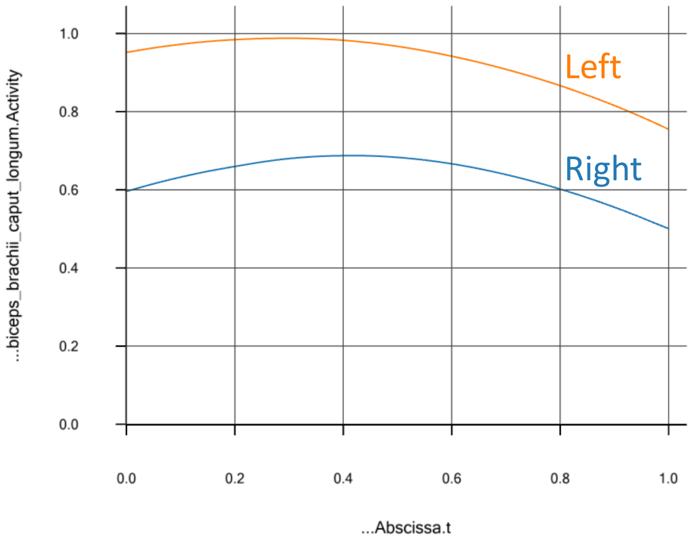
Virtual Prototyping

- Study different exoskeleton models
  - Change interface shape, attachment points

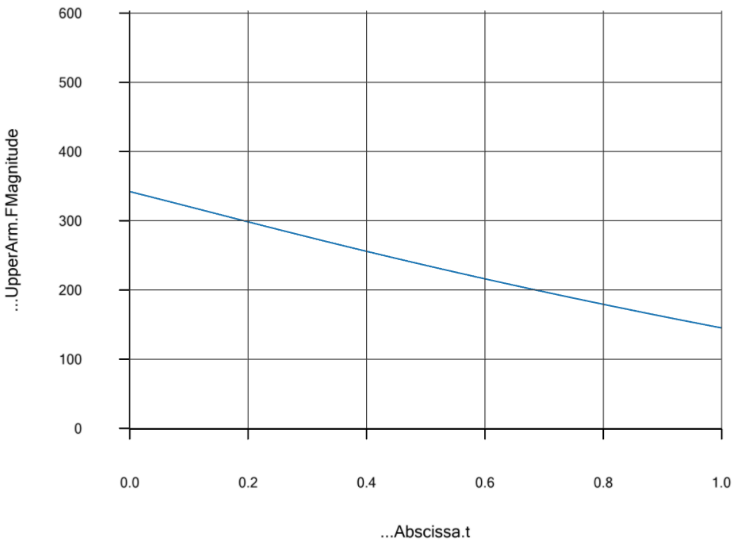




Biceps Brachii Long Head Activity



Upper Arm Interface Force (N)

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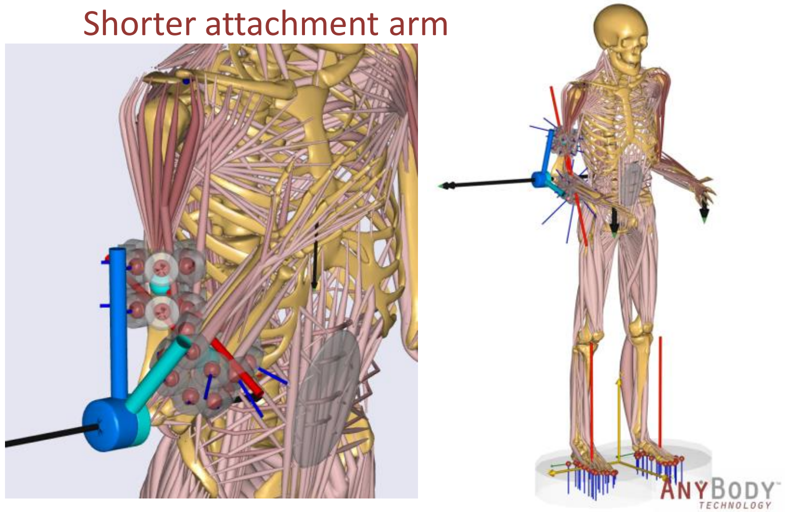
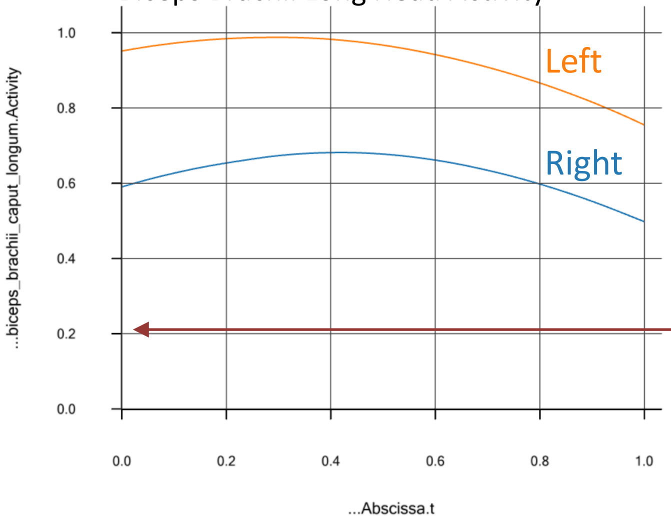
    AnyFloat UArmIntElbDist = 0.20;
    AnyFloat LArmIntElbDist = 0.15;
    AnyFloat IntElbHorDist = 0.07;
  };
};
```

Virtual Prototyping

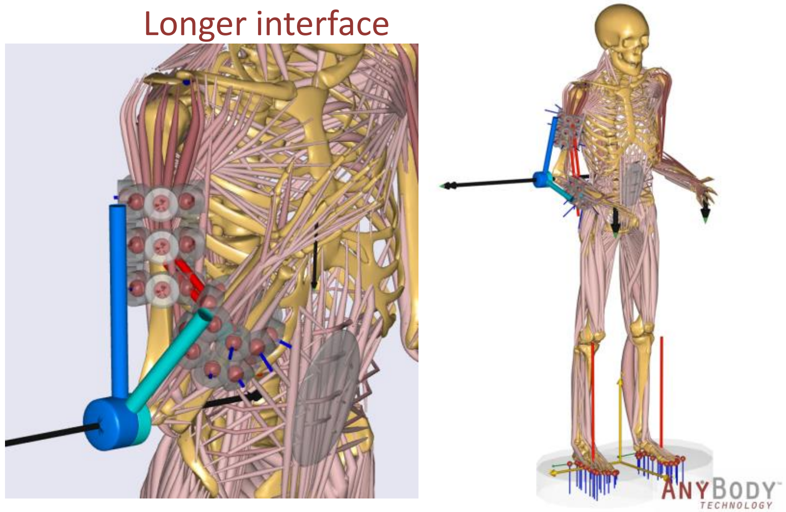
Shorter attachment arm



Biceps Brachii Long Head Activity



Longer interface



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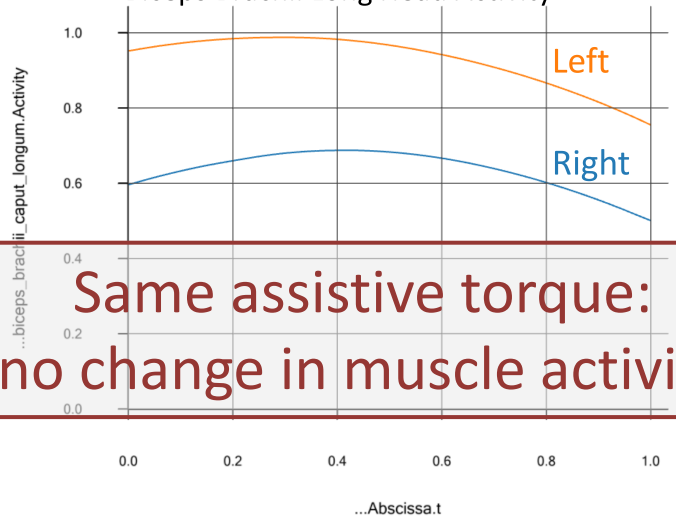
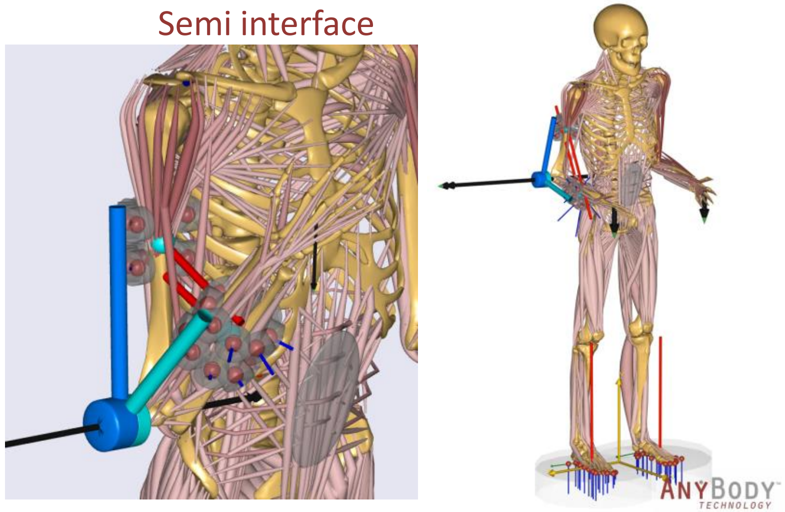
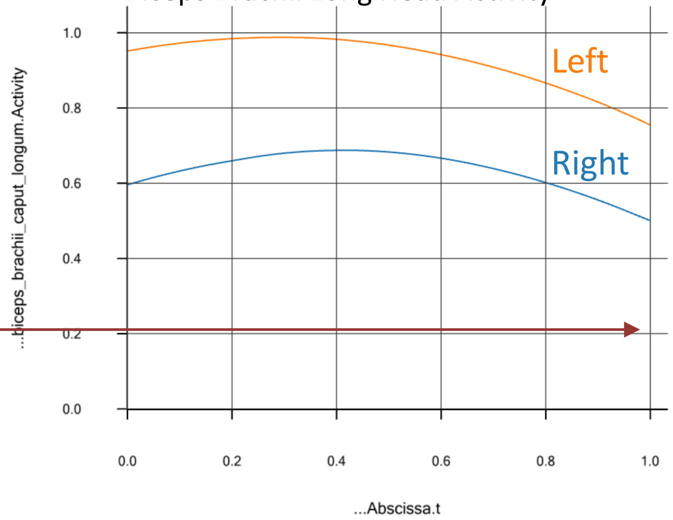


Semi interface



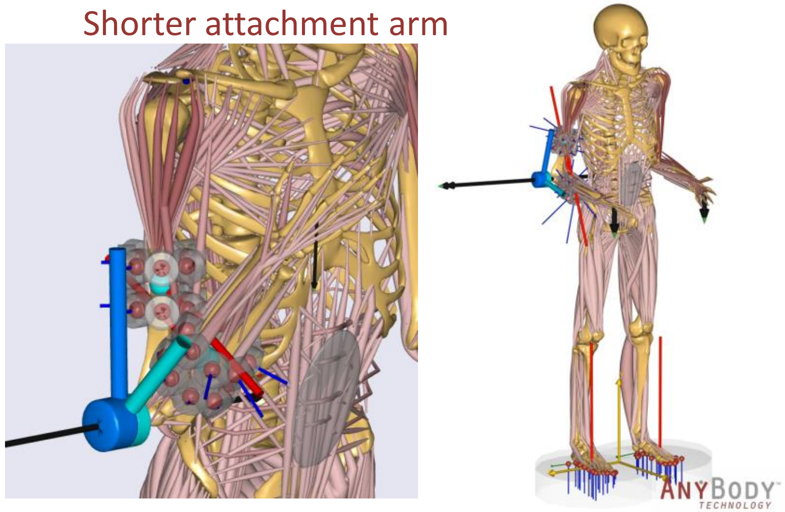
Biceps Brachii Long Head Activity



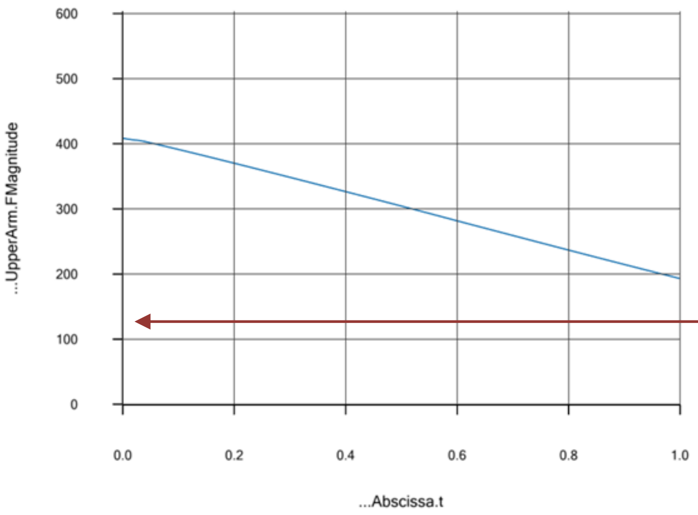
Same assistive torque:
no change in muscle activity

Virtual Prototyping

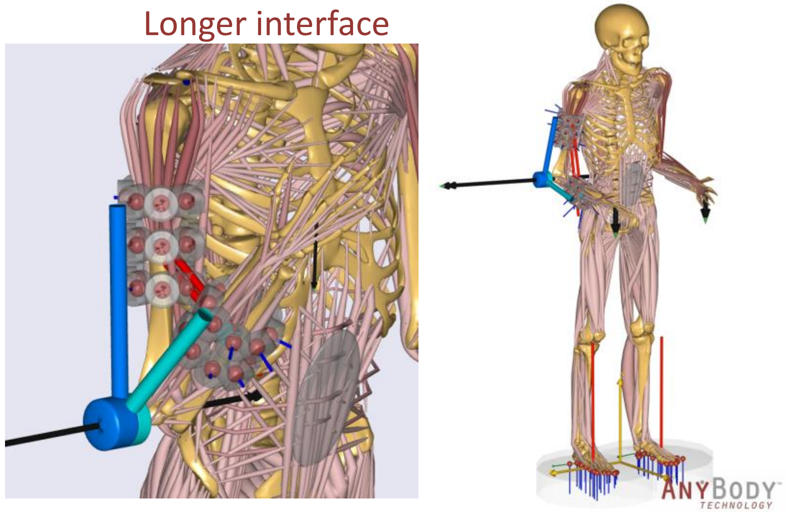
Shorter attachment arm



Upper Arm Interface Force (N)



Longer interface



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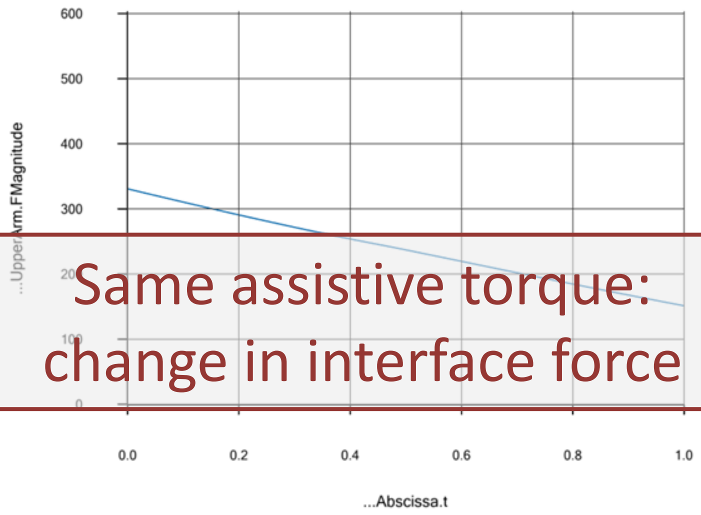
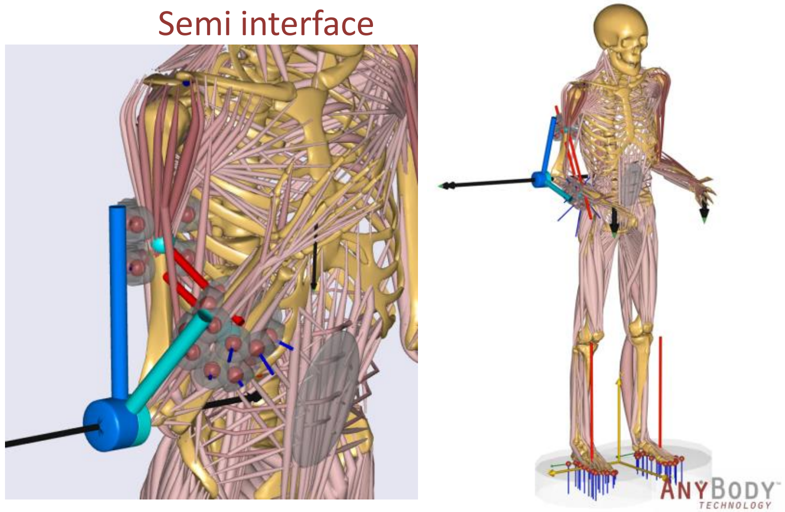


Same assistive torque:
change in interface force

Semi interface



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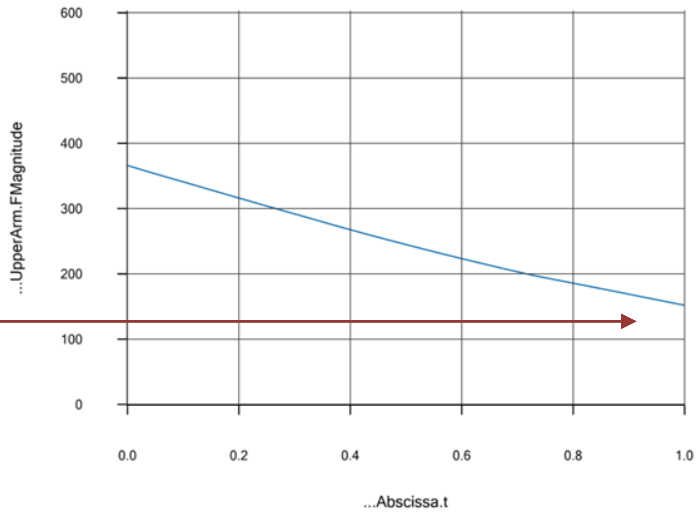
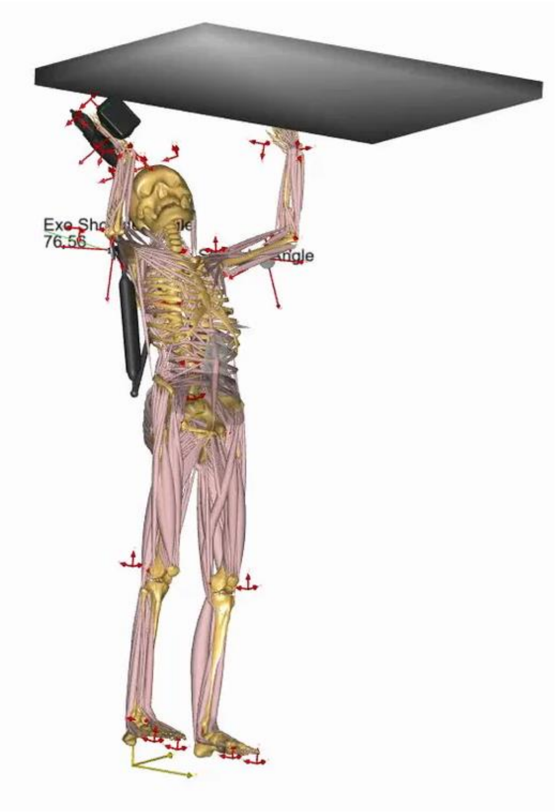


Physical Evaluation

- Lab or field trials
  - Motion data using c3d or bvh
- Model validation
  - EMG measurements
- Document exo effects
  - Change in internal body loads
- Correlate subjective and quantitative measures



L. Fritzsche et al. (2021): Assessing the efficiency of exoskeletons in physical strain reduction by biomechanical simulation with AnyBody Modeling System. Wearable Technologies, 2, E6. DOI: 10.1017/wtc.2021.5

ANYBODY TECHNOLOGY

Physical Evaluation

The An.Dy project investigated the Paexo Shoulder for overhead activity operating a hand tool

- 12 subjects experimental study
- 5 trials with and without exoskeleton
- Each trial comprised 24 poses (target points) analyzed individually
- Xsens MVN (full-body kinematics) and marker-based motion capture (tool)
- Ground reaction force measurement (optional)

Experimental study conducted at:

Institut "Jožef Stefan"
Ljubljana, Slowenia

Inria
INVENTORS FOR THE DIGITAL WORLD

iit ISTITUTO ITALIANO DI TECNOLOGIA

imk ERGONOMIE

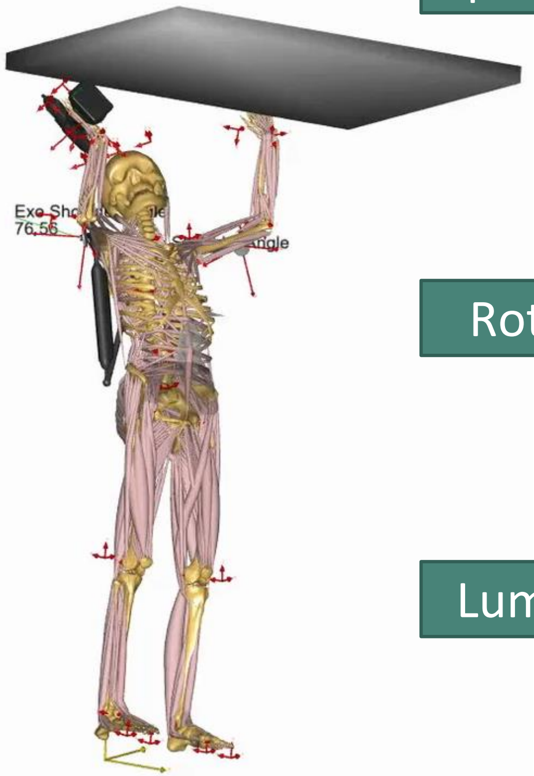
ottobock.

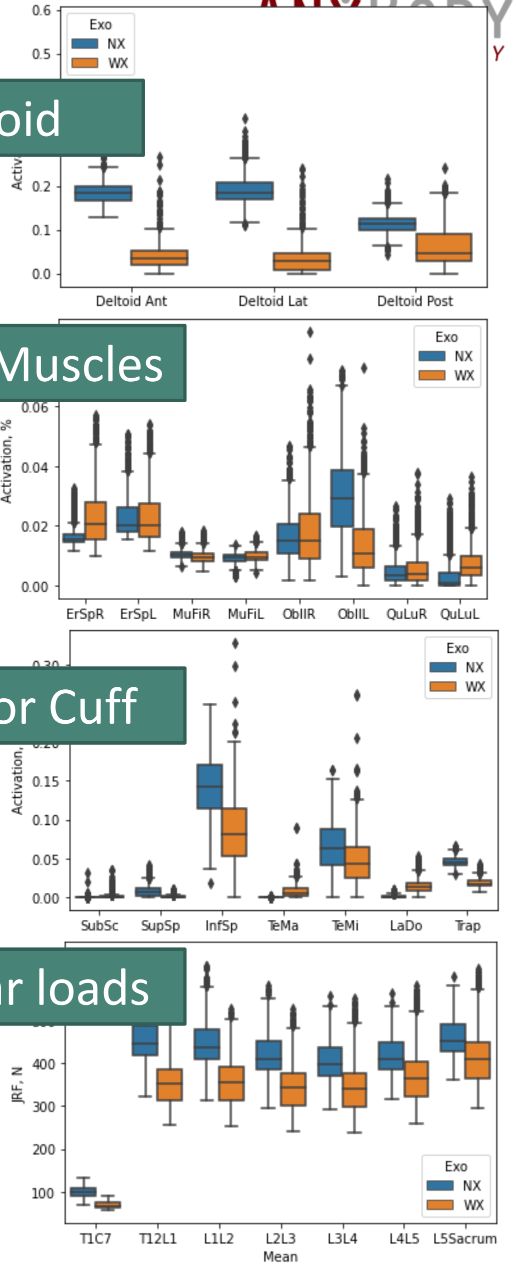
Participants:
- 12 male students
- age: 23.2 (+-1.3)
- weight: 72.6 kg (+-5.4)
- height: 179.3 cm (+-5.9)

P. Maurice et al. (2019). Objective and Subjective Effects of a Passive Exoskeleton on Overhead Work. IEEE Transactions on Neural Systems and Rehabilitation Engineering. Online ISSN: 1558-0210. DOI: 10.1109/TNSRE.2019.2945368

Physical Evaluation

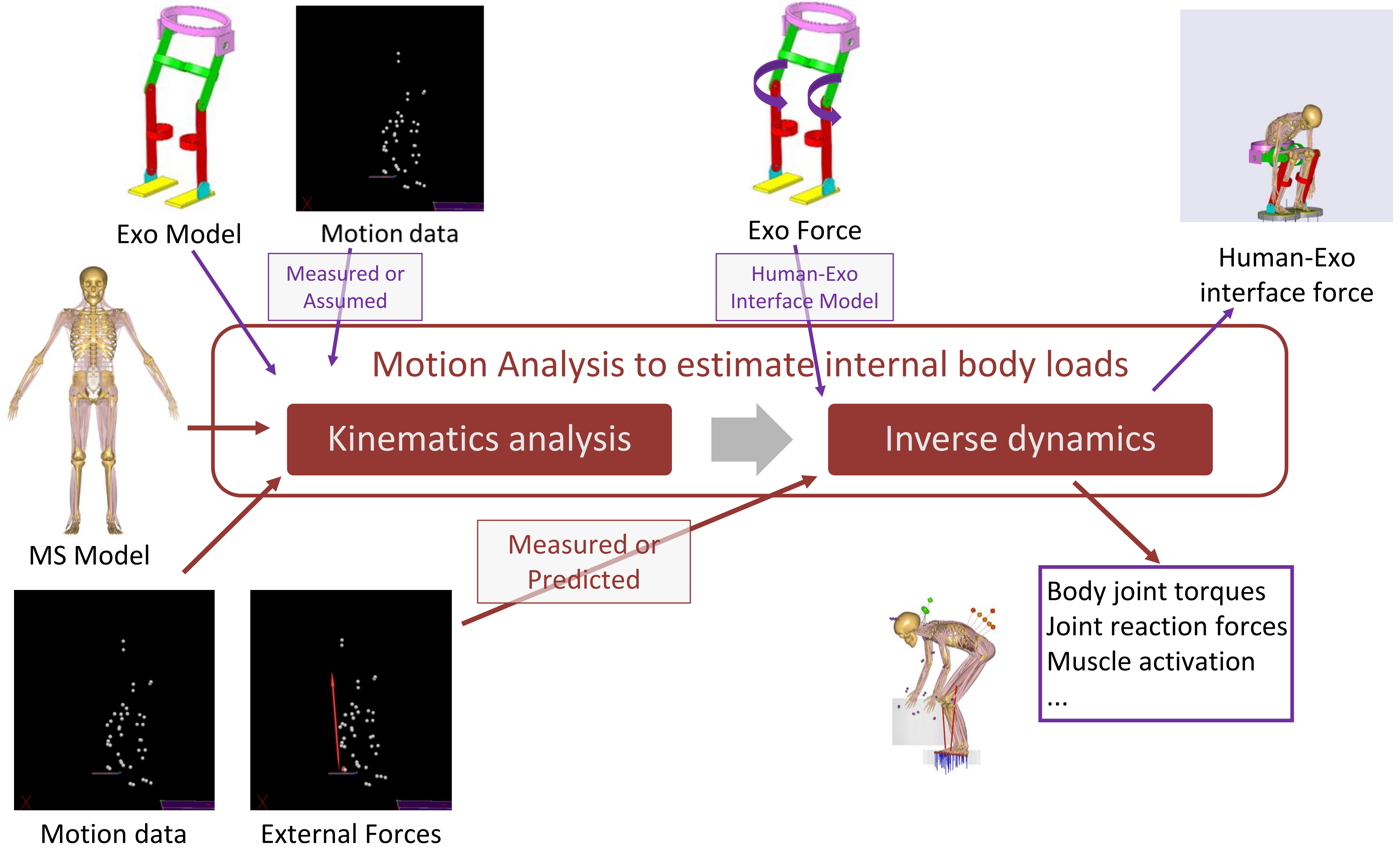
- Approximately 3000 trials simulated in AnyBody
- Individual and grouped analyses
- Detailed output for muscles and joint loading compared between With-Exo and No-Exo case
- Systematic search for beneficial and potential side-effects





L. Fritzsche et al. (2021): Assessing the efficiency of exoskeletons in physical strain reduction by biomechanical simulation with AnyBody Modeling System. Wearable Technologies, 2, E6. DOI:10.1017/wtc.2021.5

Modelling the human-exoskeleton connection


Exo Model
Motion data
Measured or Assumed
Exo Force
Human-Exo Interface Model
Human-Exo interface force
Motion Analysis to estimate internal body loads
Kinematics analysis
Inverse dynamics
MS Model
Measured or Predicted
Body joint torques
Joint reaction forces
Muscle activation
...
Motion data
External Forces

Human-Exoskeleton Connection

Kinematics:

- Constrained to human
- MoCap driven
- Hybrid

Kinetics:

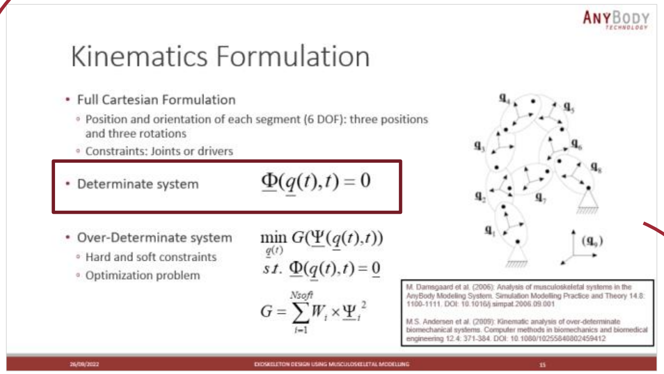
- Reaction forces
- Contact elements

"Connecting an exoskeleton to a human model". AnyBody Wiki page. https://github.com/AnyBody/support/wiki/Connecting-an-exo-skeleton-to-a-human-model

Kinematics

Constrained to Human

- Each exoskeleton segment introduces 6 DOF in the model
  - Additional DOFs = Additional constraints
- Constraints:
  - Joints between exoskeleton segments
  - Joints/constraints between human and exoskeleton
    - Many ways to define!


Kinematics Formulation

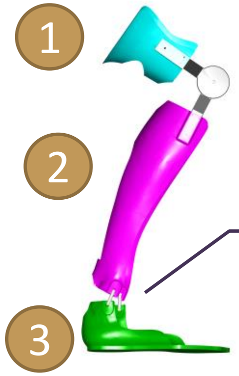
- Full Cartesian Formulation
  - Position and orientation of each segment (6 DOF): three positions and three rotations
  - Constraints: Joints or drivers
- Determinate system $\underline{\Phi}(\underline{q}(t),t)=0$
- Over-Determinate system
  - Hard and soft constraints
  - Optimization problem

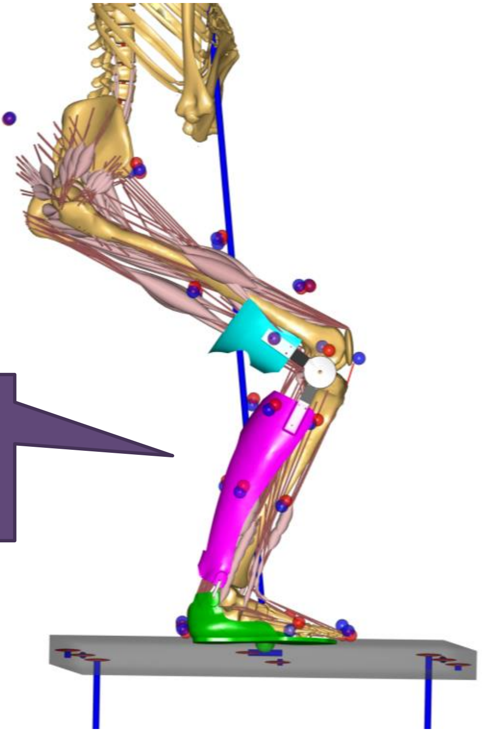
$$\min_{\underline{q}(t)} G(\underline{\Psi}(\underline{q}(t),t))$$
$$s.t.\ \underline{\Phi}(\underline{q}(t),t)=\underline{0}$$
$$G=\sum_{i=1}^{Nsoft} W_i \times \underline{\Psi}_i^{\,2}$$

M. Damsgaard et al. (2006): Analysis of musculoskeletal systems in the AnyBody Modeling System. Simulation Modelling Practice and Theory 14.8: 1100-1111. DOI: 10.1016/j.simpat.2006.09.001

M.S. Andersen et al. (2009): Kinematic analysis of over-determinate biomechanical systems. Computer methods in biomechanics and biomedical engineering 12.4: 371-384. DOI: 10.1080/10255840802459412

18 dofs = 6 * 3 segs
5 constraints = Exo Knee revolute joint
5 constraints = Exo Ankle revolute joint
8 constraints = Human-Exo connection



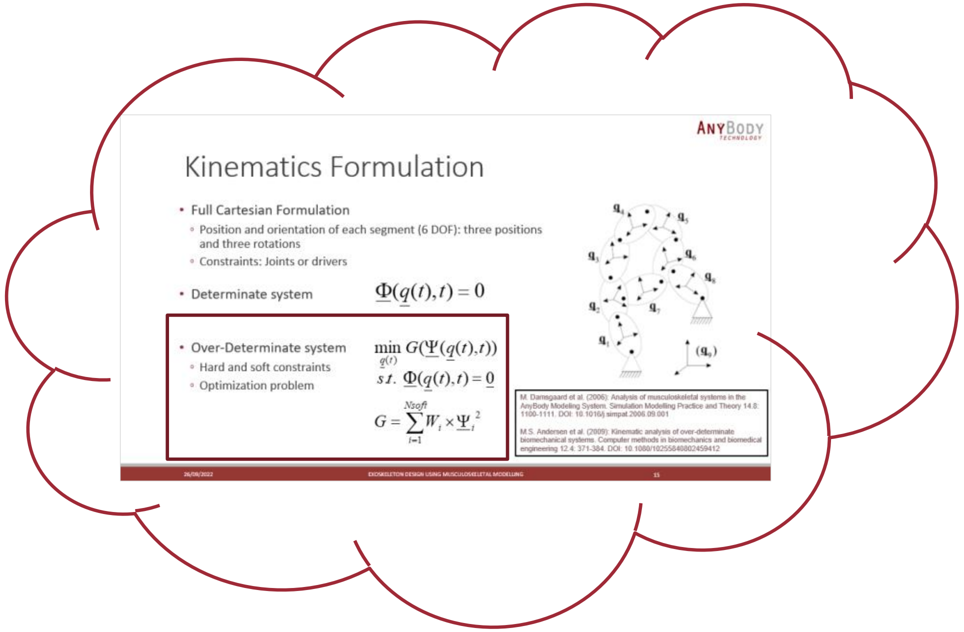


Knee Ankle Foot Orthosis (KAFO)

movaid

Kinematics

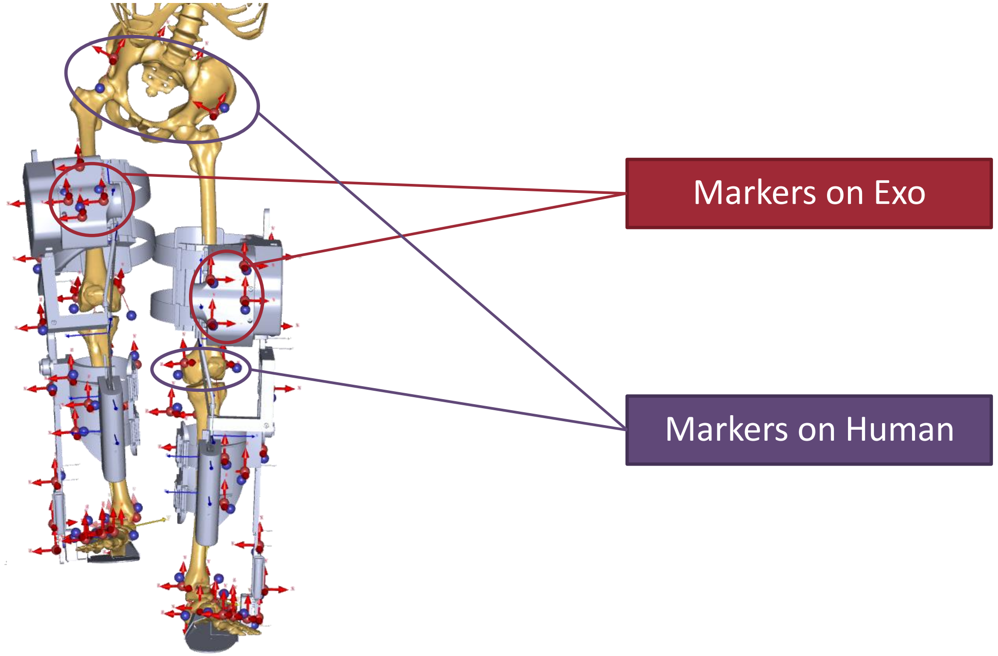
MoCap driven (c3d)



- Markers located on exoskeleton parts

- Constraints:
  - Hard constraints: Exoskeleton joints
  - Soft constraints: Exoskeleton markers

- Independent kinematics of human and exoskeleton
  - Possible to see relative motion between human and exoskeleton.

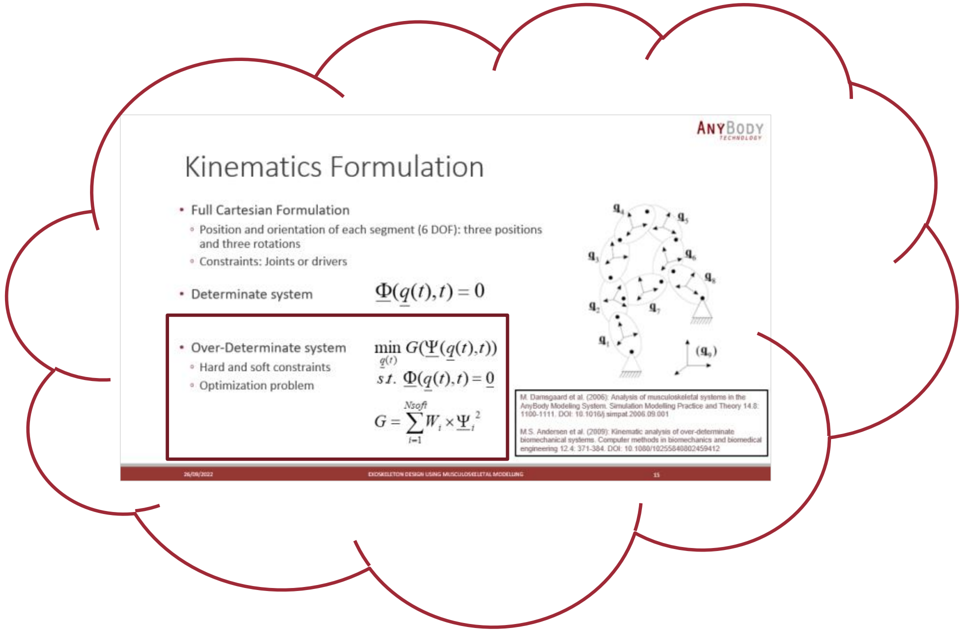


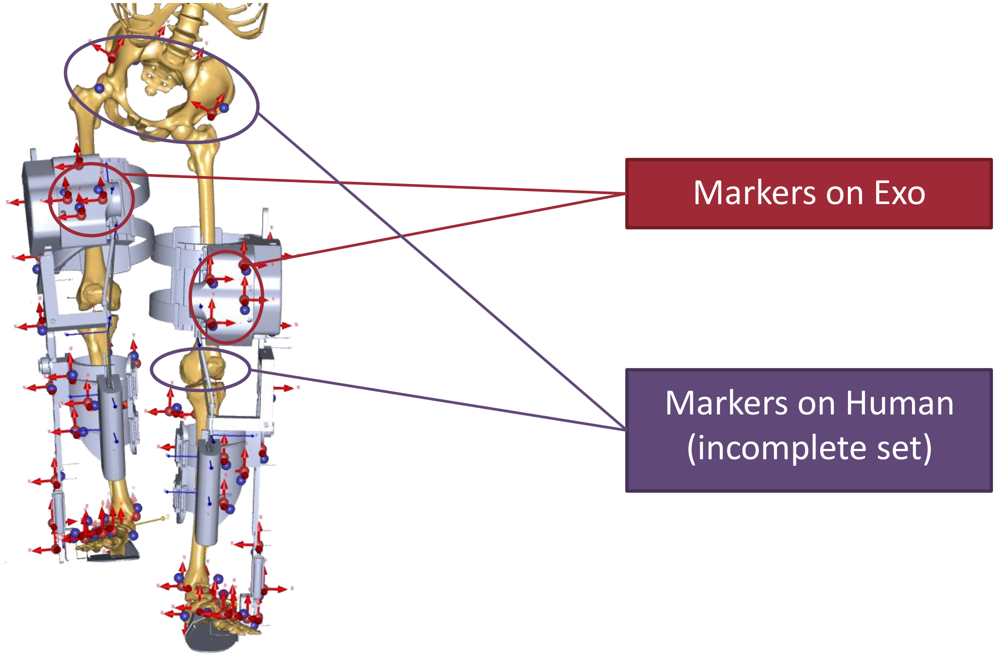
D.S. Chander et al. (2022): A comparison of different methods for modelling the physical human-exoskeleton interface. International Journal of Human Factors Modelling and Simulation 7.3-4: 204-230. DOI: 10.1504/IJHFMS.2022.124310

Kinematics

Hybrid

- Markers located on exoskeleton parts
- Impossible to capture human and exoskeleton motion independently
  - Exoskeleton covers human limb
- Constraints:
  - Hard constraints: Exoskeleton joints
  - Hard/soft constraints: Human exoskeleton connection
  - Soft constraints: Exoskeleton markers

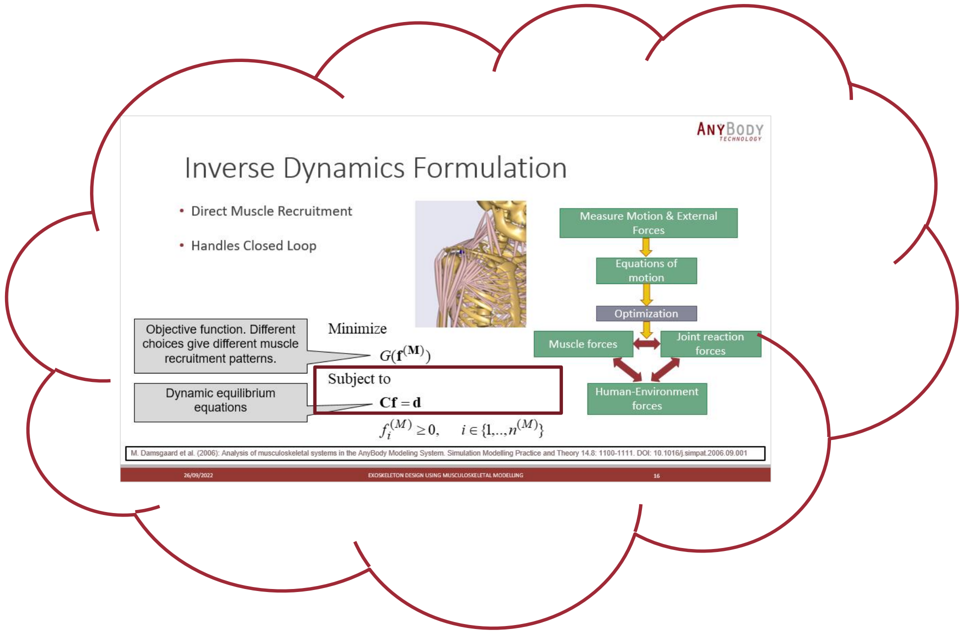


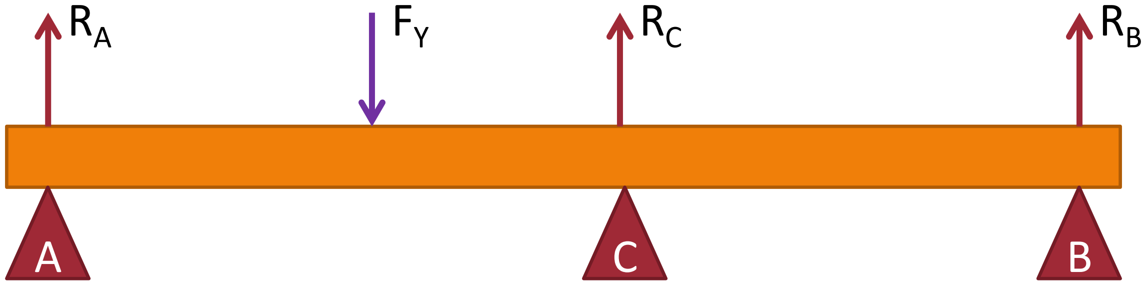


Kinetics

Reaction Forces

- Typically, associated with kinematic constraints.
  - E.g.: reactions at exoskeleton joints
- Additional Reactions = Additional constraints for Exo
  - Several ways to add reaction forces
  - Limitations in investigation of interface force



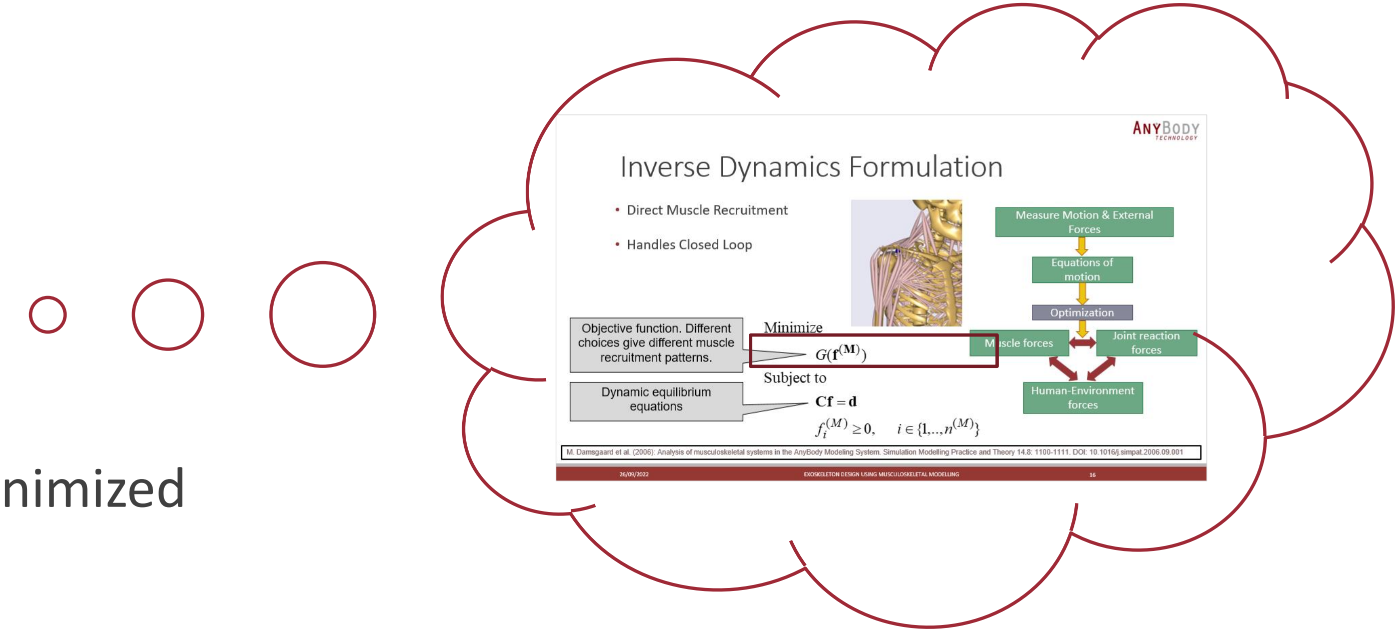


3 unknowns: R_A, R_B and R_C

2 equations: $\sum F = 0$, and $\sum M = 0$

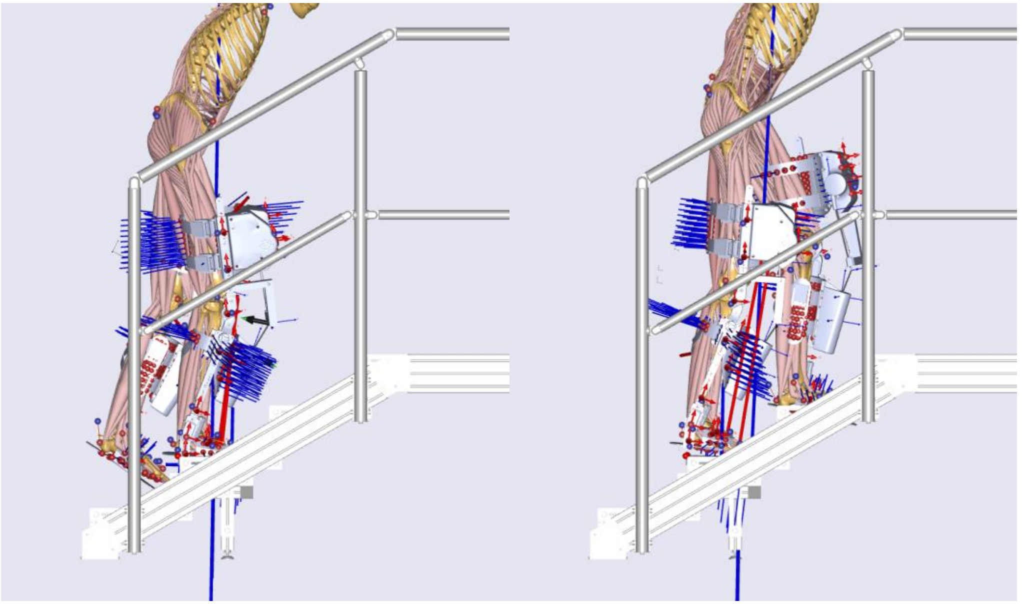
→ Infinitely many solutions!

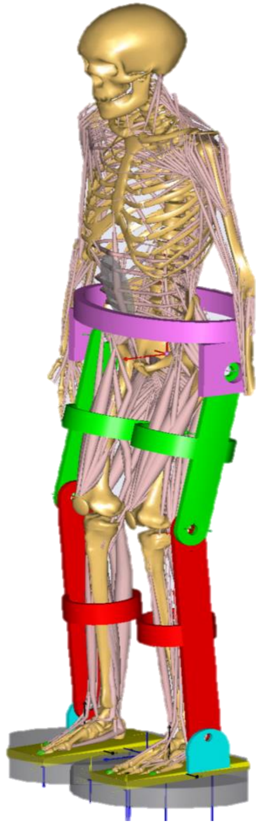
Kinetics



Recruited Actuators

- Optimization-based: Minimized recruited force.
- Not limited by additional exo DOFs
- Up to 6DOF interface force at each interface
- Rigid-body contact forces
  - Normal and friction force





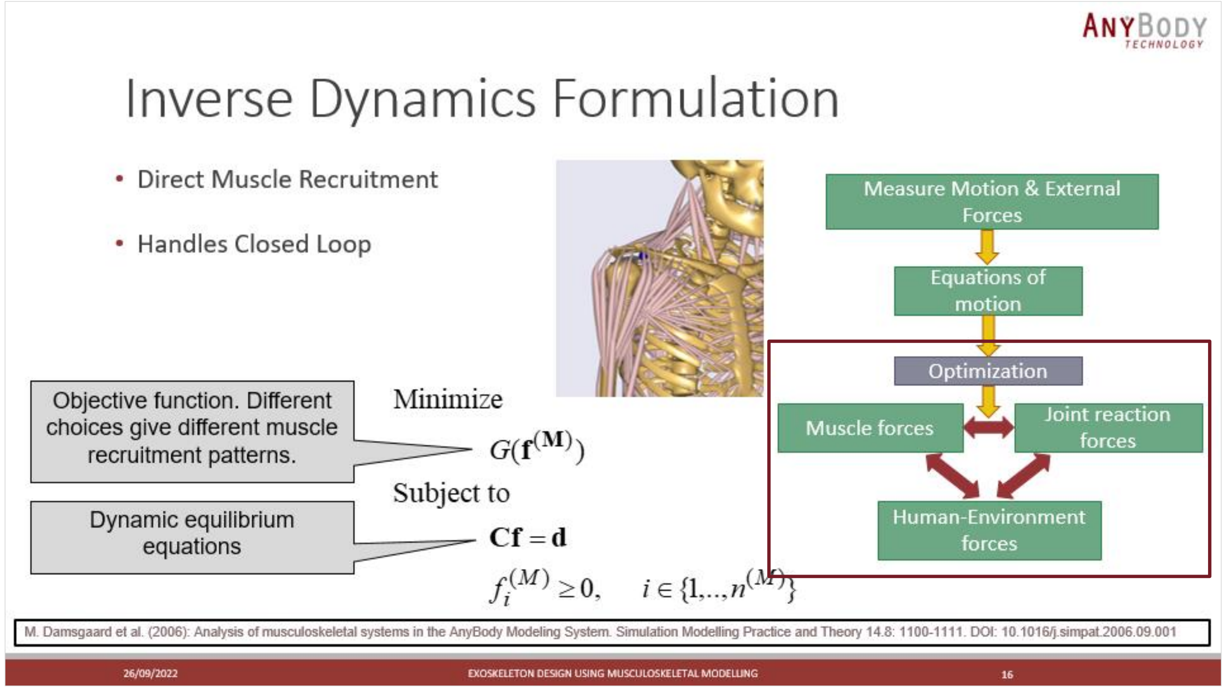
D.S. Chander et al. (2022): A comparison of different methods for modelling the physical human-exoskeleton interface. International Journal of Human Factors Modelling and Simulation 7.3-4: 204-230. DOI: 10.1504/IJHFMS.2022.124310

"SitToStand_Exo" model. Model from a previous webcast.
https://github.com/AnyBody/support/wiki/Example-from-the-exoskeleton-webcast

Practical Issues

Issues in interface modelling

- Direct muscle recruitment
  - Possible interaction between interface force and muscle force
- Critical analysis of results
  - Sensitivity analysis
- Possible causes
  - Joint misalignment



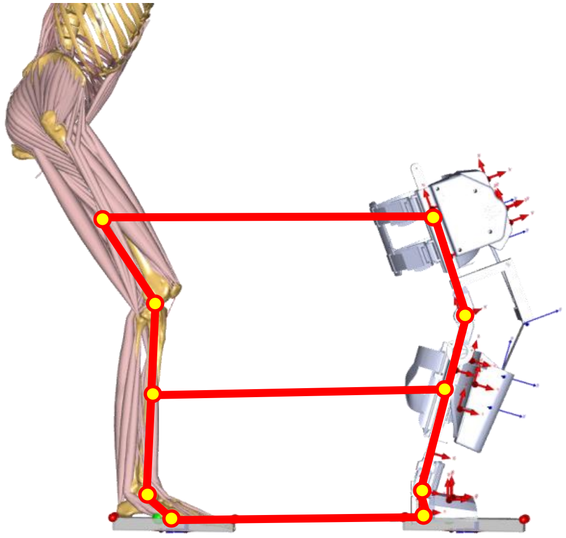
Practical Issues

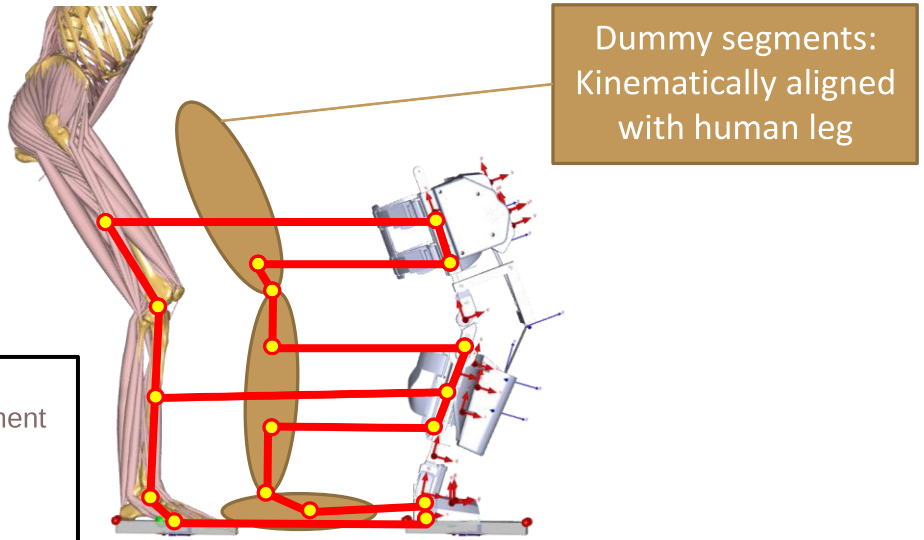
Joint Misalignment

- Actual effects:
  - Misaligned movement
  - Reduced assistance
  - Parasitic interface force

- Model effects:
  - Depends… unexpected outcomes possible

- How to deal with joint misalignment in the model:
  - Kinematic constraints ensuring alignment
  - Dummy segments ensuring kinetic alignment





Further reading on dummy segments:

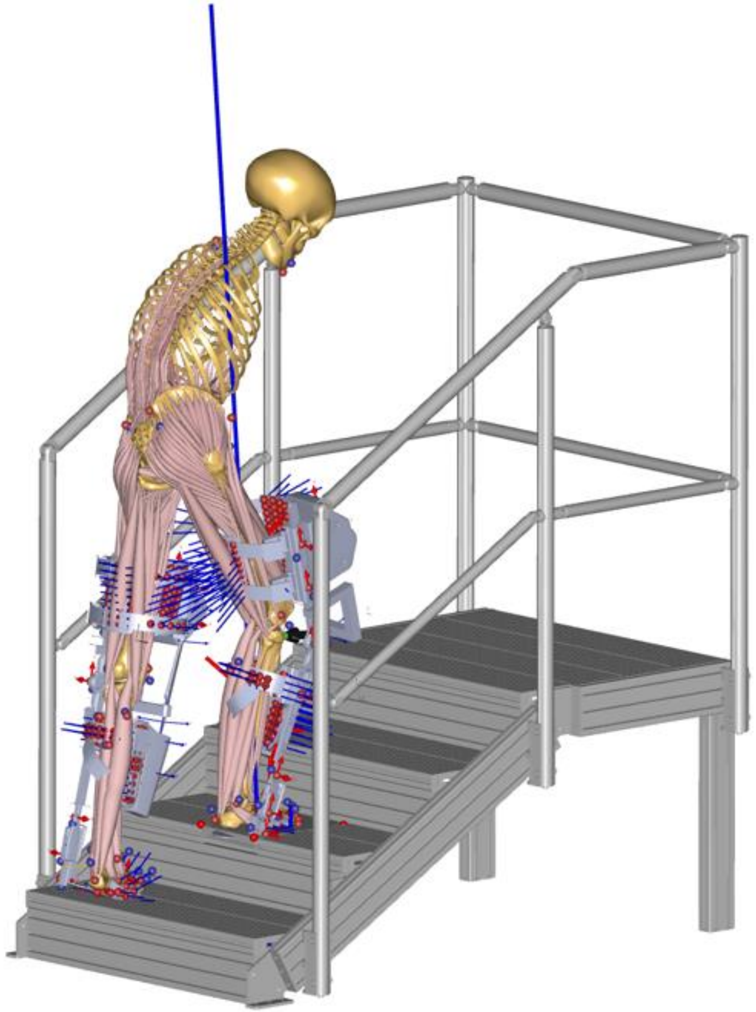
D.S. Chander et al. (2023): Simulating the Dynamics of a Human-Exoskeleton System Using Kinematic Data with Misalignment Between the Human and Exoskeleton Joints. In International Symposium on Computer Methods in Biomechanics and Biomedical Engineering (pp. 65-73). DOI: 10.1007/978-3-031-10015-4_6

D.S. Chander et al. (2022): A comparison of different methods for modelling the physical human-exoskeleton interface. International Journal of Human Factors Modelling and Simulation 7.3-4: 204-230. DOI: 10.1504/IJHFMS.2022.124310

Stair Assist Exoskeleton Model

- Available on GitHub
  - https://github.com/AnyBody/StairAssist_Exo

- Acknowledgements:
  - Department of Mechanical and Aerospace Engineering, Politecnico di Torino (ITALY)
  - Faculty of Engineering, Leipzig University of Applied Sciences (GERMANY)
  - Department of Materials and Production, Aalborg University (DENMARK)



Relevant Publications:

D.S. Chander et al. (2023): Simulating the Dynamics of a Human-Exoskeleton System Using Kinematic Data with Misalignment Between the Human and Exoskeleton Joints. In International Symposium on Computer Methods in Biomechanics and Biomedical Engineering (pp. 65-73). DOI: 10.1007/978-3-031-10015-4_6

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M. Böhme et al. (2022): Preliminary Biomechanical Evaluation of a Novel Exoskeleton Robotic System to Assist Stair Climbing. Applied Sciences, 12(17), 8835. DOI: 10.3390/app12178835

Conclusion

- Applications of MS models in exoskeleton design
  - Conceptual stage
  - Virtual prototyping
  - Physical evaluation

- Modelling of human-exoskeleton connection
  - Kinematics:
    - Kinematic constraints
    - Mocap based
    - Hybrid setup (incomplete marker set on human)
  - Kinetics
    - Reaction forces
    - Recruited actuators
    - Issues in interface modelling

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Events

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  - The future of personalized orthopaedics: Kinematic modeling to restore the premorbid knee functionality through robotic-assisted TKA

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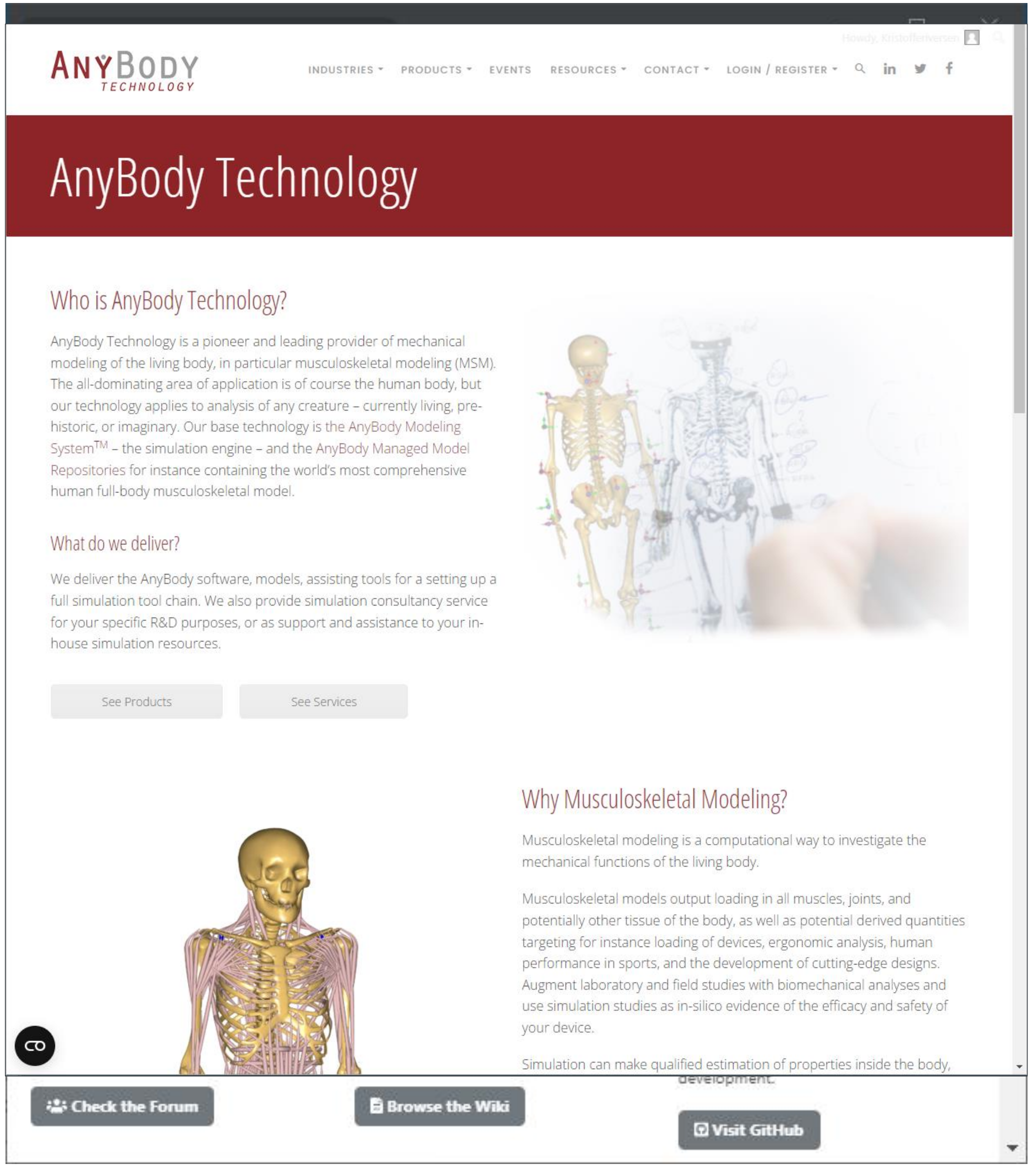

Thank you for your attention
- Time for questions