

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

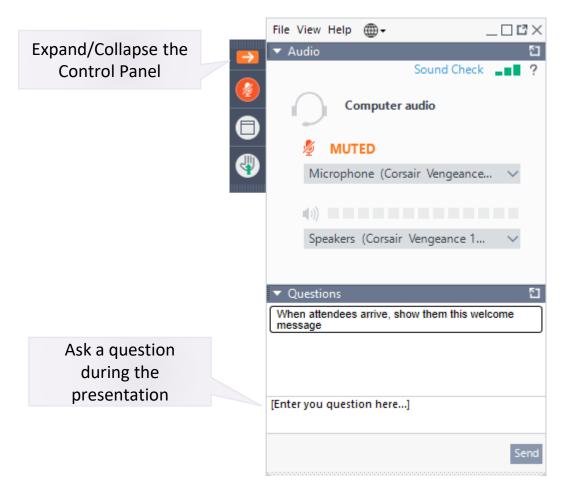


Control Panel

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



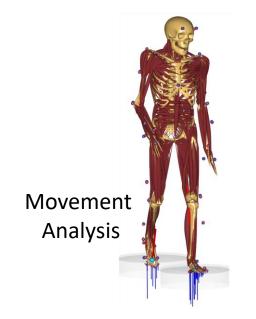




Body Loads

- Joint moments
- Muscle forces
- Joint reaction forces

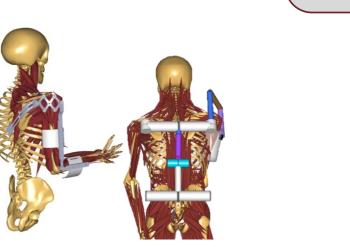
AnyBody - License - C:\Users\ki\Documents\a	mm^Application\Examples\StandingPosturePredictionWithLoad\StandingPosturePrediction.main.any	- 0	×
File Edit View Operation Tools Win	dow Help		
🐚 🛍 🗳 💾 🚰 X 🗇 🗂 A+ 🏓 H	bad Execute: ■ ▶ ▶ RunApplication ▼		
📜 💯 🐺 🕺 Replay: 🔳 🖬 💌	1 1		
Active Tools: Main.HumanModel: Configuration	n		
Model 👻 🛪 🗙	StandingPosturePrediction.main.any 4 b x Model View 1	* Q 1	×
Model Operations Files ← → 9 0 ↔ ← ← Main ← HumanModel ← Input Parameters ← Model ← Konematc, Pre, Study ← Study ← Study ← Widget Departon ← Widget Departon ← Widget Departon	<pre>//This is model which can predict the posture as a consequence of applied loads in hands. //t does this y minimizing joint torques and apply balance drivers which account for external //pojied loads. // * not issue to point concern and the following drivers: // * fortiers which minimize the following drivers: // * fortiers instin contact with the ground, built the foot stance area. // * fortiers mich minimize to an object, of which positioning can be altered using widgets // * fortiers mich mich as a force vector applied on the object and/or a force vector // * fortiers model has a force vector applied on the object being held between the hands with a zerc // * fortier mich model // * tord the tord tord the model tord tord tord tord tord tord tord tord</pre>		ICHOIDS
Information • a x Main AnyMainFolder	<pre>sinclude "Jointlimit/Salance_texplate_foot_arce.any" sinclude "MinTorqueClass/NinTorqueClass.any" //Suitch to define if load is applied to both hands or a single hand. //Suitch to define if load is applied to both lands, loadInleftHand. define LoadInRightHand 1 </pre>		
Model Tree: Main	Kain Lin 31 Col29		
	Output Output 00 Design variables there been updated. 0	↓ 0)	×
			¥

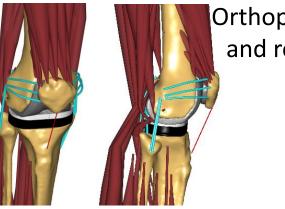




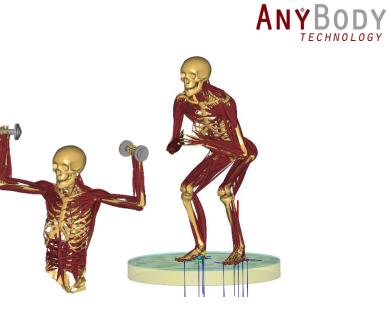
Product optimization design

ANYBODY Modeling System

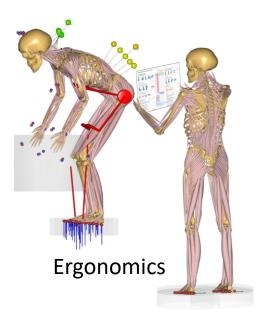




Orthopedics and rehab



Sports

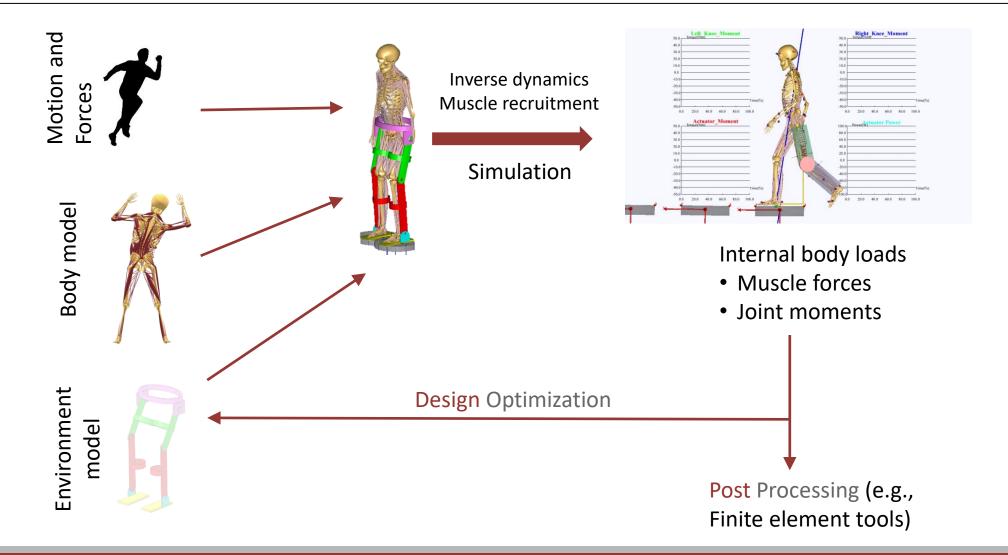


Assistive

Devices



AnyBody Modeling System

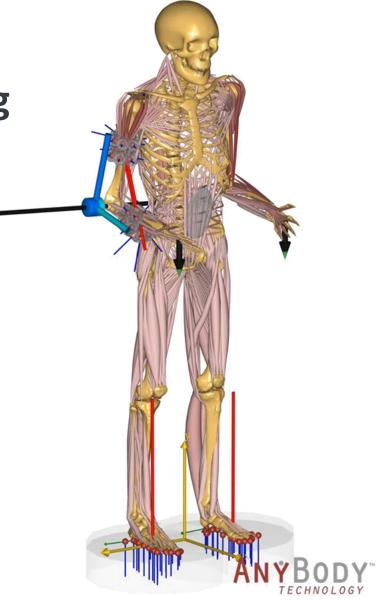




An introduction to exoskeleton design using musculoskeletal modeling

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

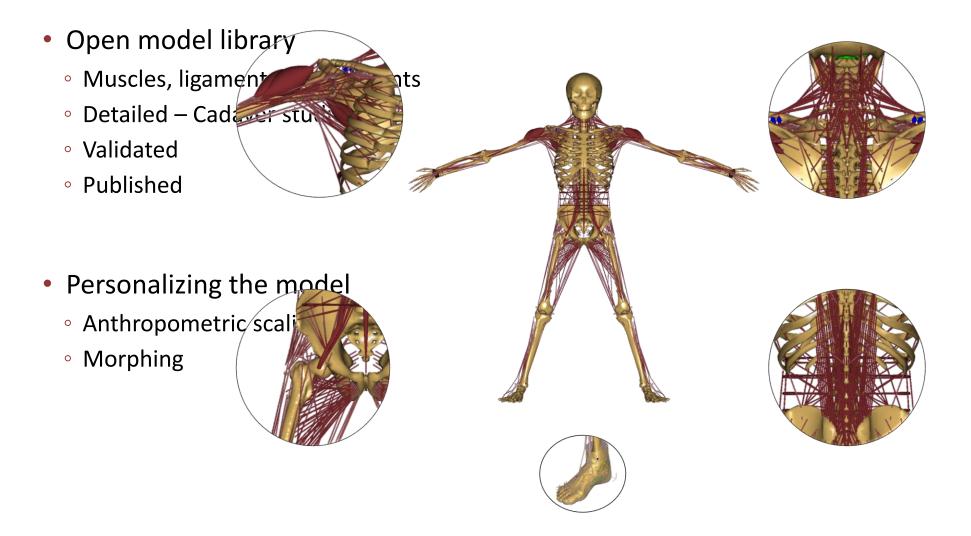
AnyBody Modeling System

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

AnyBody - License - C:\Users\ki\Documents\ar	nmr/Application/Examples/StandingPosturePredictionWithLoad/StandingPosturePrediction.main.any	- 🗆 🗙				
File Edit View Operation Tools Wind						
in in 🖕 💾 ど 🖾 🗗 â l 🗛 🍠 🖷 -	Real Load : Execute ■ ▶ ▶ RunApplication -					
📜 📜 🎜 🎽 Replay: 🔲 💽 💽						
Active Tools: Main.HumanModel: Configuration						
	StandingPosturePrediction.main.any 4 b × Model View 1	▼ # × 2				
Model Operations Files ← → 및↓ ∞ ← Main ← HumanModel ← HumanModel ← Konger ← Study ← Study ← Study ← KongerOperation ← Model ←	<pre>//This is a model which can predict the posture as a consequence of applied loads in hands. //T does this by minimizing joint torques and apply balance drivers which account for external //poplied loads. // The model is driven by a combination of the following drivers: // The model is driven by a combination of the following drivers: // * Fret model is driven by a combination of the following drivers: // * Fret model to an object, of which position can be controlled by widgets // * The two type of loads can be applied, either a fixed weight of the object and/or a force vector // The current model has a force vector applied on the object being held between the hands with a zerc // * Try to drag (click and drag) one of the widgets in the ModelView (seen as small coordinate syste // * Try to drag (click and drag) one of the widgets in the ModelView (seen as small coordinate syste // * When the widget is release the model will run the analysis</pre>	nctions				
Information v a x Main AnyMainFolder	<pre>#include "libdef.any" #include "jointlimit/Balance_template_foot_area.any" #include "MinTorqueClass/MinTorqueClass.any" //Switch to define if load is applied to both hands or a single hand. //Three combinations LoadInRightHand,LoadInLeftHand #define LoadInRightHand,LoadInLeftHand,LoadInLeftHand</pre>					
Model Tree:	Kain Lin 31 Col 29					
	Main En S1 Col.29 Output 0	▼ a ×				
Parada						

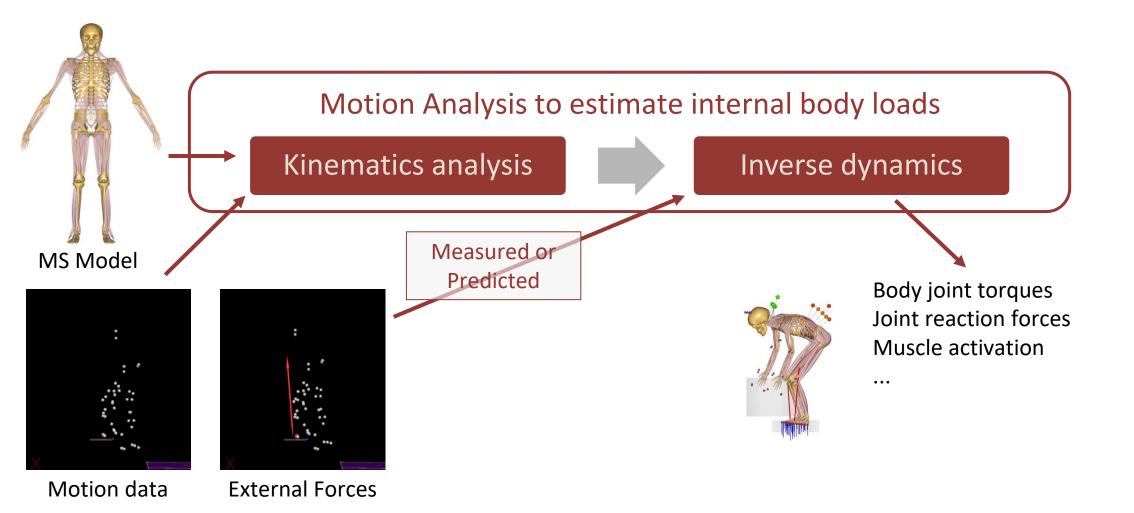


The AnyBody Managed Model Repository™





Workflow





Motion

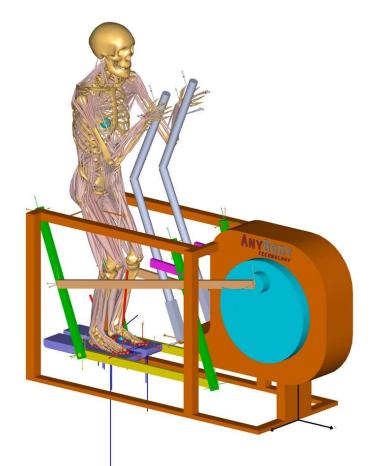
- Free motion
 - Standard MoCap (C3D files)
 - BVH files (joint angles)
- Environment driven
 - Man-machine interface
- Predicted motion
 - Posture optimization
- Force-dependent motion
 - Internal joint displacement





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

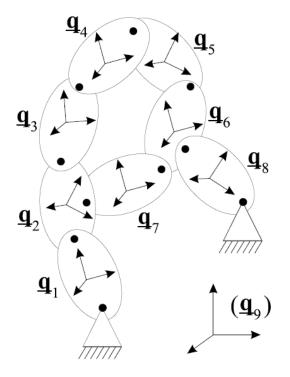
- Full Cartesian Formulation
 - Position and orientation of each segment (6 DOF): three positions and three rotations
 - Constraints: Joints or drivers
- Determinate system

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

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

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

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

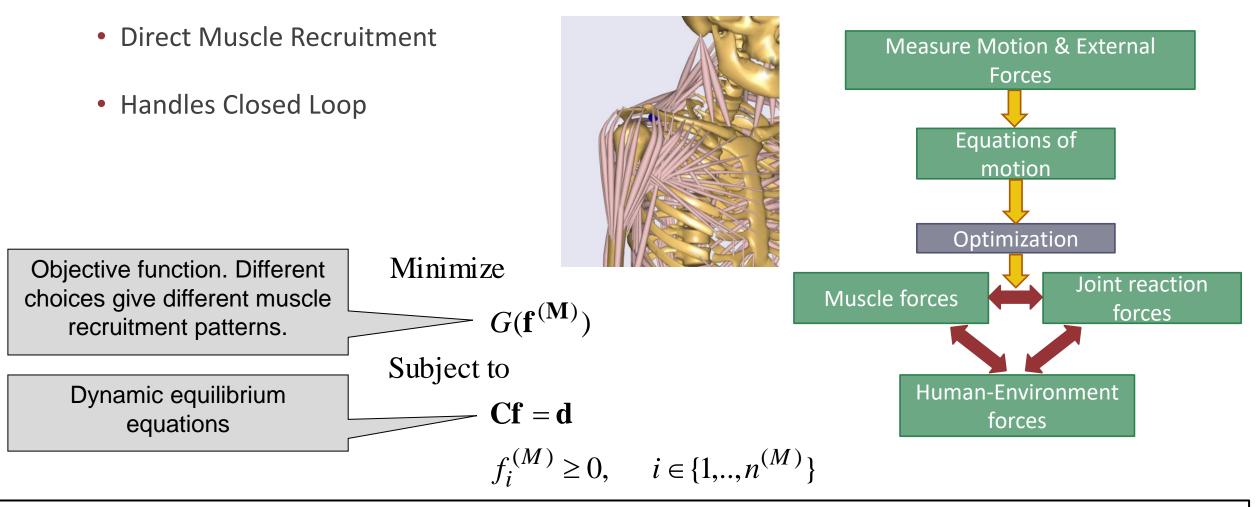


M. Damsgaard et al. (2006): Analysis of musculoskeletal systems in the AnyBody Modeling System. Simulation Modelling Practice and Theory 14.8: 1100-1111. DOI: 10.1016/j.simpat.2006.09.001

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



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



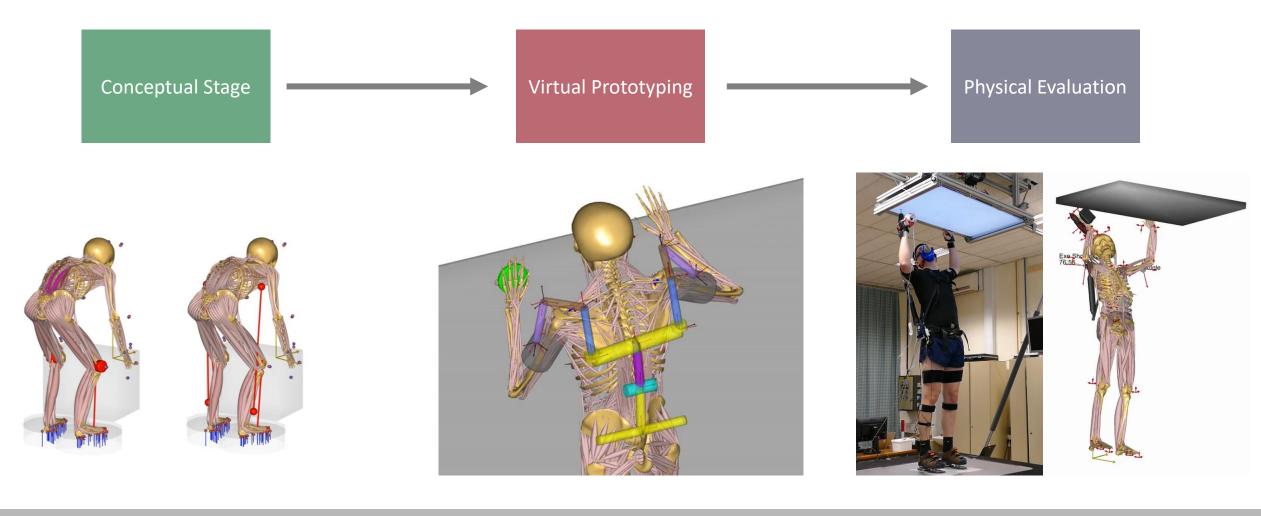
Design Questions

- 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

- 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



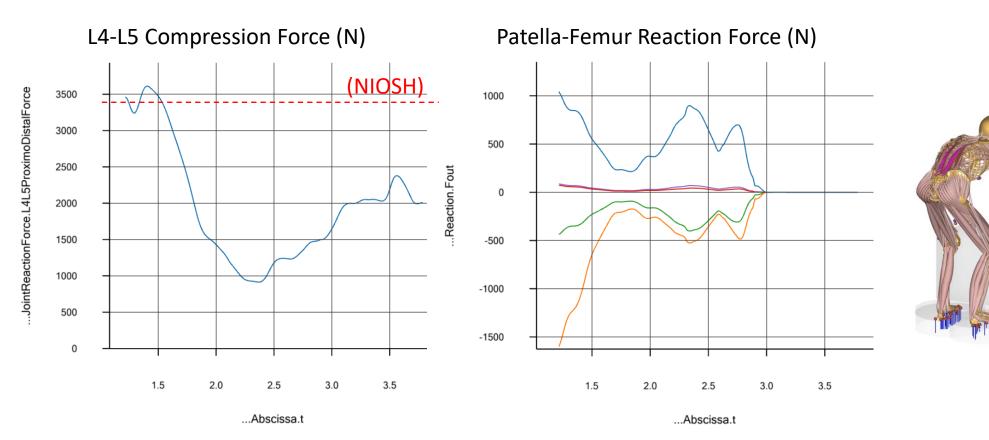


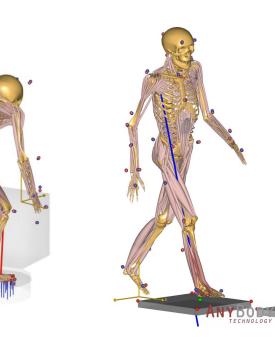


Conceptual Exoskeleton

- Task Analysis
 - Establish baseline and target

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





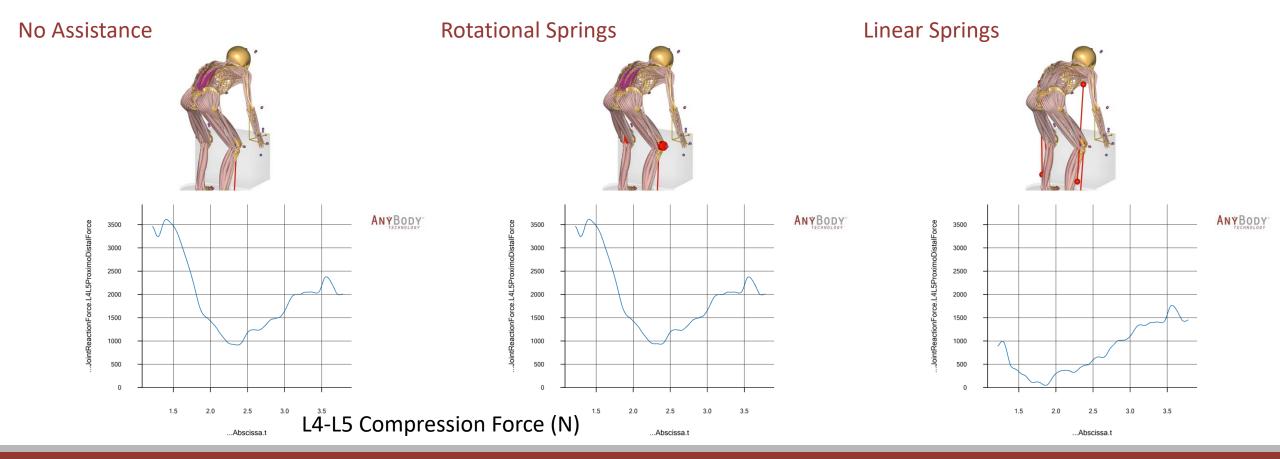


Conceptual Exoskeleton

• Study different concepts

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

Idealized Assistance. NO DETAILED CAD MODEL



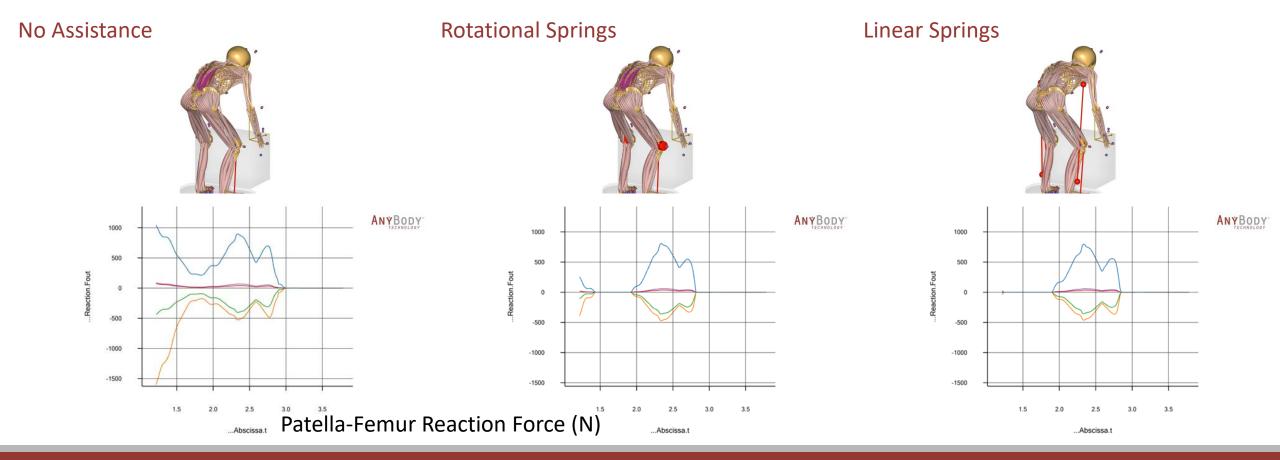


Conceptual Exoskeleton

• Study different concepts

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

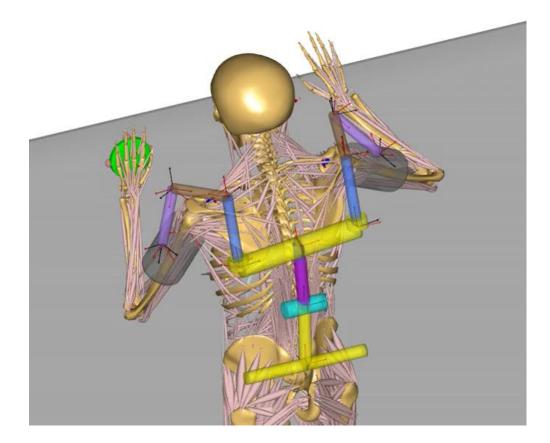
Idealized Assistance. NO DETAILED CAD MODEL





Virtual Prototyping Stage

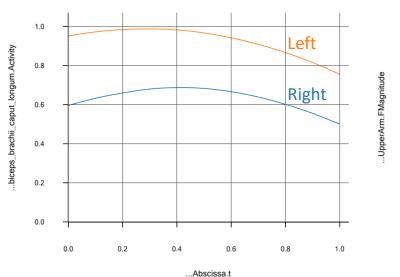
- CAD model
 - Mass and inertia properties
 - Detailed mechanism
- Exo geometry
 - Kinematic alignment
 - Attachment points
- Interface shape
 - Area of contact
 - Shape
- Assitive Torque





Virtual Prototyping

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



Biceps Brachii Long Head Activity

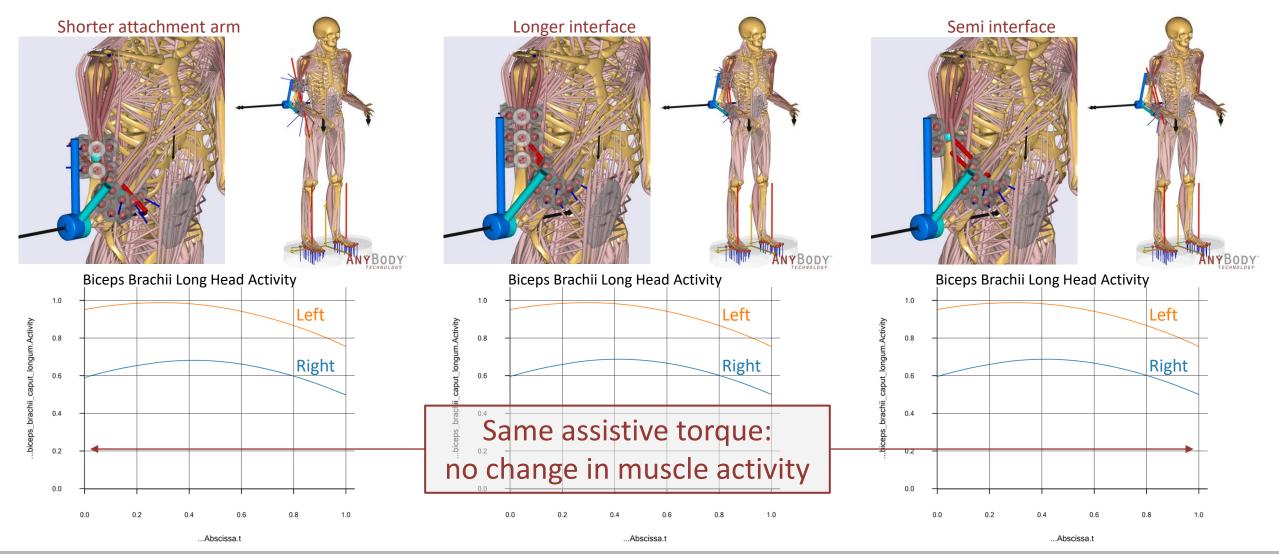
Upper Arm Interface Force (N)

Main.Model = {

AnyFolder ModelParameters = {
 AnyFloat HandLoad = {0,-100,0};
 AnyFloat ExoSpringConstant = 30;
 AnyFloat UArmIntElbDist = 0.20;
 AnyFloat LArmIntElbDist = 0.15;
 AnyFloat IntElbHorDist = 0.07;

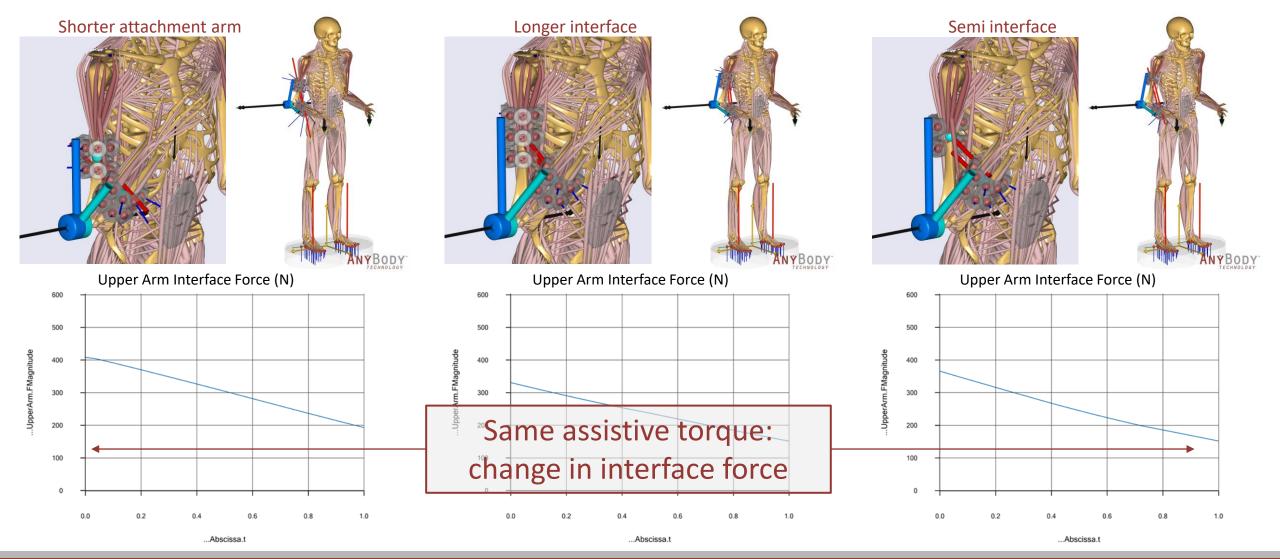


Virtual Prototyping





Virtual Prototyping

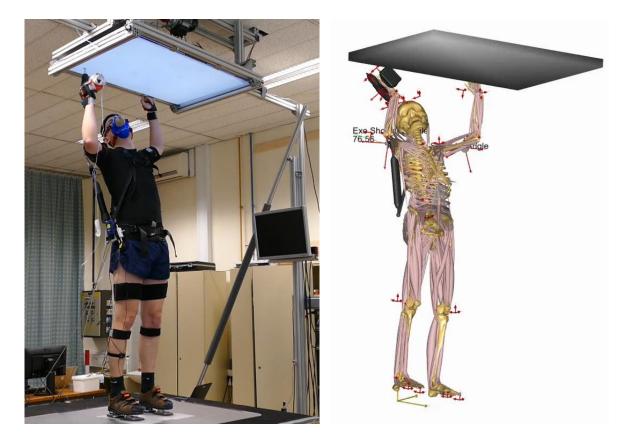


27



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



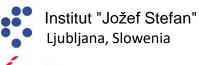
Physical Evaluation

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 markerbased motion capture (tool)
- Ground reaction force measurement (optional)



Experimental study conducted at:





IT ISTITUTO ITALIANO DI TECNOLOGIA

ottobock.

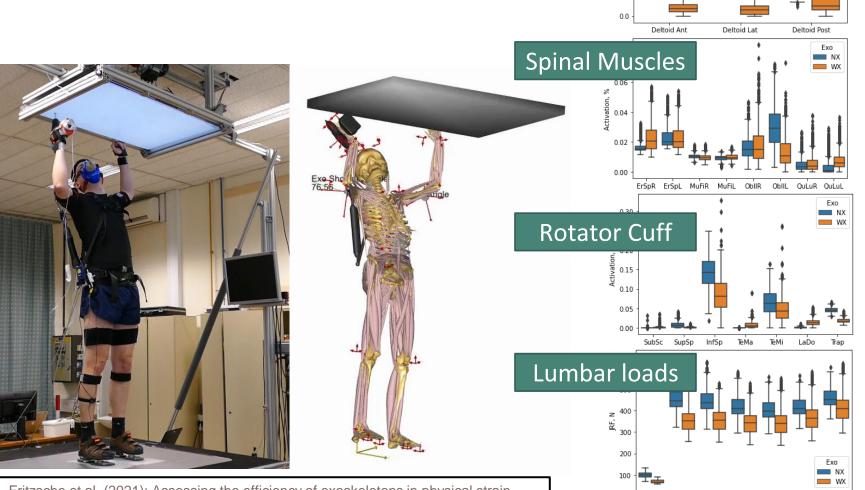
Participants:

- 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

T1C7

T12L1

L1L2

L2L3

L3L4

L4L5 L5Sacrum

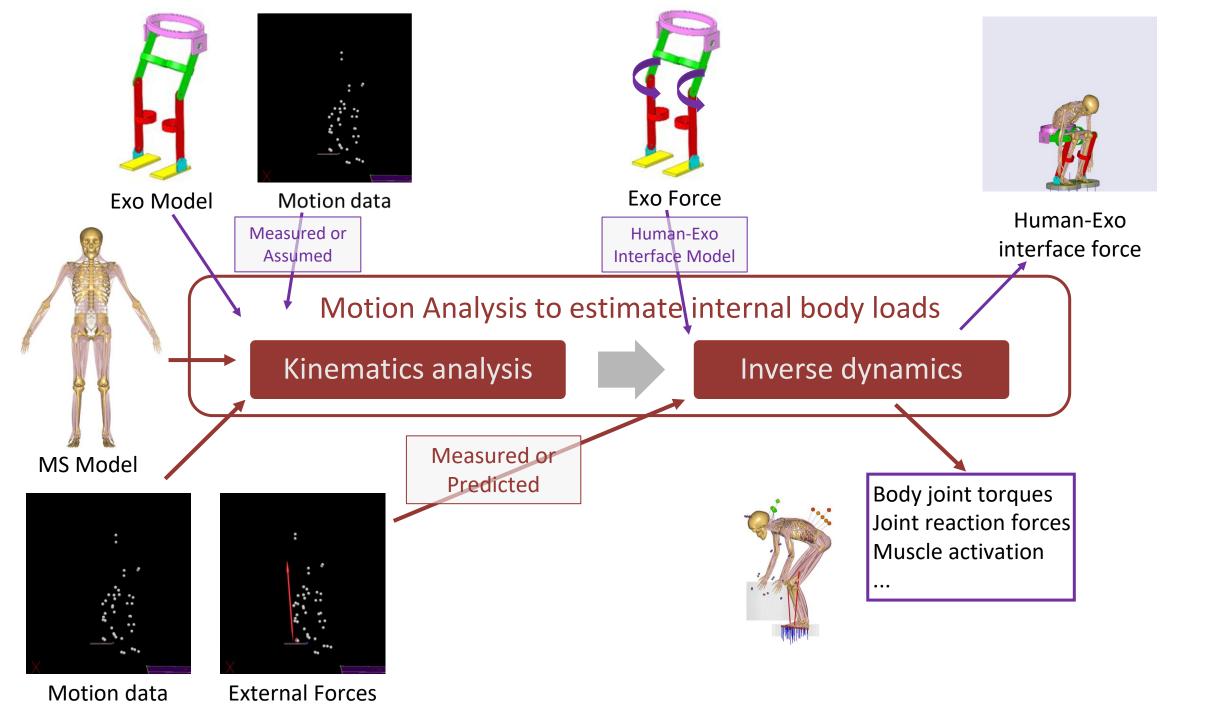
Exo

Deltoid

τ¥ 0.2



Modelling the humanexoskeleton connection





Human-Exoskeleton Connection

Kinematics:

Kinetics:

- Constrained to human
- MoCap driven
- Hybrid

- 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!

ANYBODY ANYBODY Kinematics Formulation **Full Cartesian Formulation** Position and orientation of each segment (6 DOF): three positi and three rotations Constraints: Joints or driv $\underline{\Phi}(q(t),t) = 0$ Determinate system $\min G(\Psi(q(t),t))$ Over-Determinate syste Hard and soft constraint $st. \Phi(q(t),t) = 0$ $G = \sum W_i \times \Psi$ 18 dofs = 6 * 3 segs 5 constraints = Exo Knee revolute joint 5 constraints = Exo Ankle revolute joint 8 constraints = Human-Exo connection **Revolute Joint:** 5 constraints Human-Exo connection: 8 constraints **Revolute Joint:** 5 constraints movako Knee Ankle Foot Orthosis (KAFO)

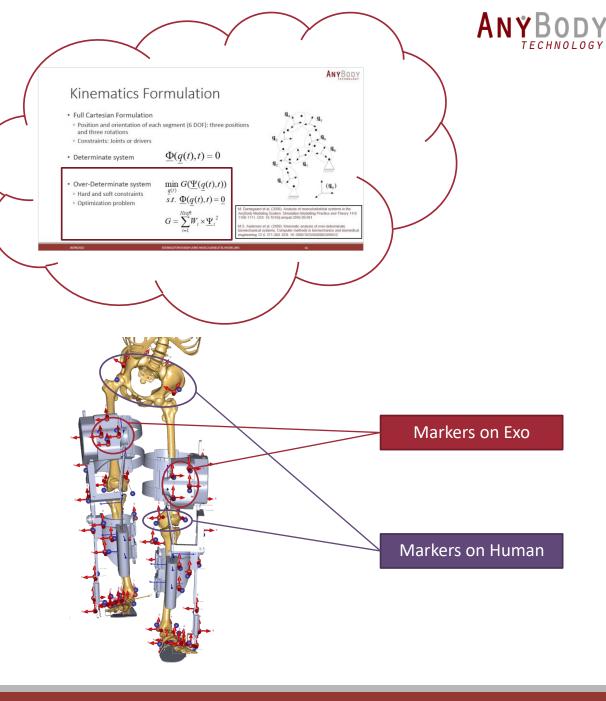
EXOSKELETON DESIGN USING MUSCULOSKELETAL MODELLING

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.

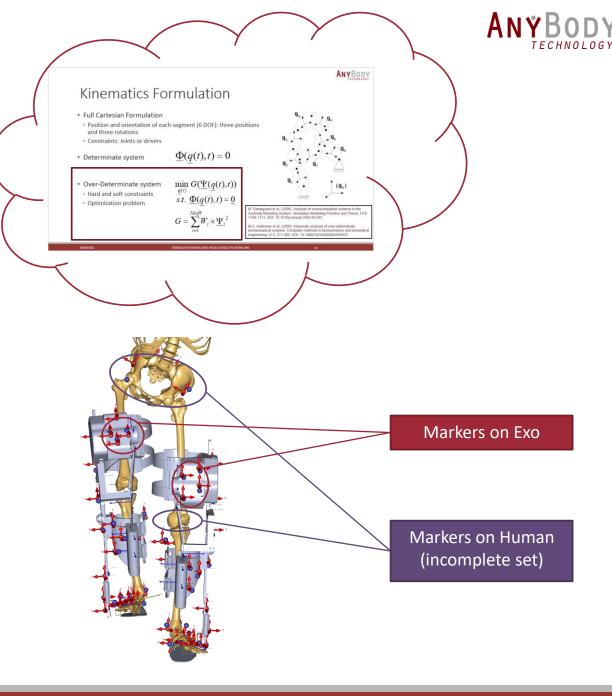
D.S. Chander et al. (2022): A comparison of different methods for modelling the physical human-exoskeleton interface. International Journal of Human Factors Modelling and Simulation 7.3-4: 204-230. DOI: 10.1504/IJHFMS.2022.124310



Kinematics

Hybrid

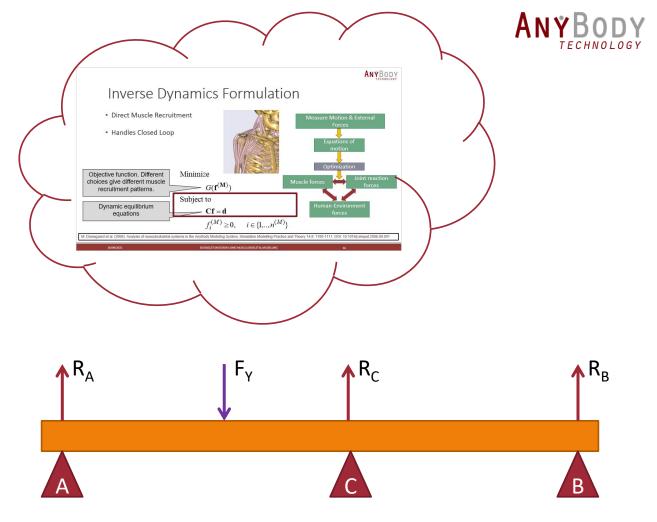
- Markers located on exoskeleton parts
- Impossible to capture human and exoskeleton motion independently
 - Exoskeleton covers human limb
- Constraints:
 - Hard constraints: Exoskeleton joints
 - Hard/soft constraints: Human exoskeleton connection
 - Soft constraints: Exoskeleton markers



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: $\Sigma F = 0$, and $\Sigma M = 0$

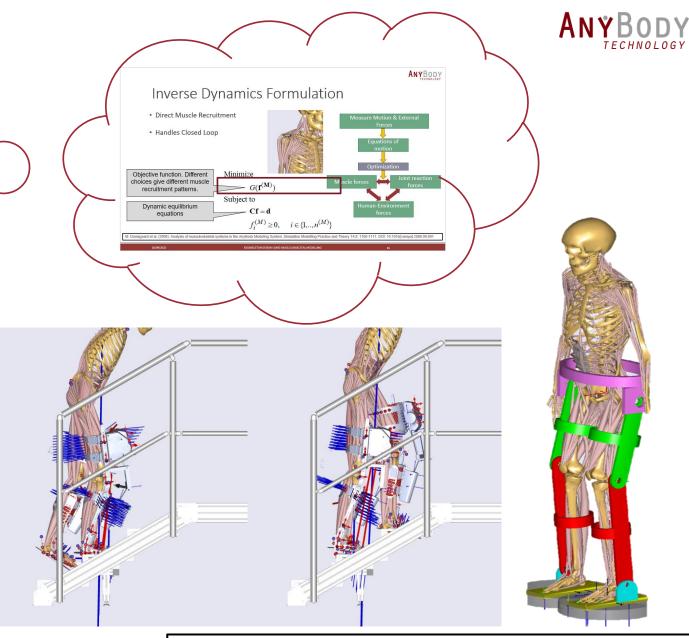
 \rightarrow Infinitely many solutions!

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



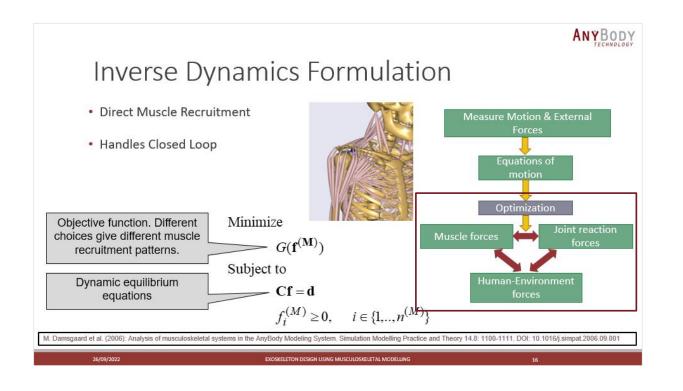
"SitToStand_Exo" model. Model from a previous webcast. https://github.com/AnyBody/support/wiki/Example-from-the-exoskeleton-webcast



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

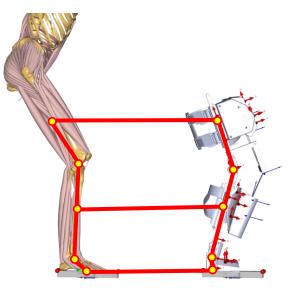
Joint Misalignment

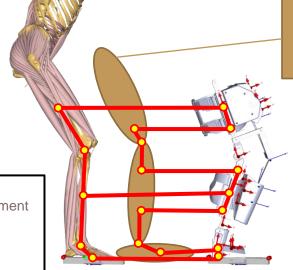
- Actual effects:
 - Misaligned movement
 - Reduced assistance
 - Parasitic interface force
- Model effects:
 - Depends... unexpected outcomes possible
- How to deal with joint misalignment in the model:
 - Kinematic constraints ensuring alignment
 - Dummy segments ensuring kinetic alignment

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





Dummy segments: Kinematically aligned with human leg



Stair Assist Exoskeleton Model

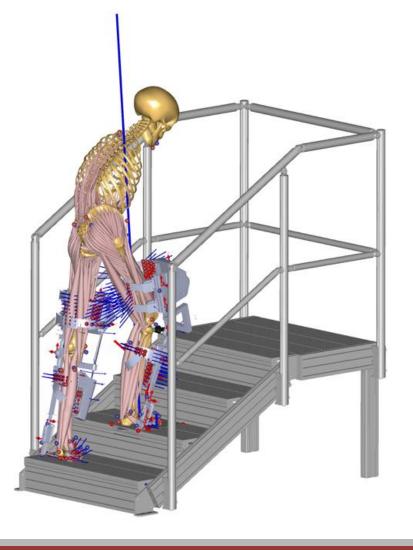
- Available on GitHub
 - <u>https://github.com/AnyBody/StairAssist_Exo</u>
- Acknowledgements:
 - Department of Mechanical and Aerospace Engineering, Politecnico di Torino (ITALY)
 - Faculty of Engineering, Leipzig University of Applied Sciences (GERMANY)
 - Department of Materials and Production, Aalborg 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

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

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

www.anybodytech.com

• Events, Webcast library, Publication list, ...

www.anyscript.org

• Wiki, Blog, Repositories, Forum

Events

Webcast:

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

Meet us? Send email to sales@anybodytech.com

Want to present? Send email to ki@anybodytech.com





AnyBody

INDUSTRIES * PRODUCTS * EVENTS RESOURCES * CONTACT * LOGIN / REGISTER * Q in 🕊

AnyBody Technology

Who is AnyBody Technology?

AnyBody Technology is a pioneer and leading provider of mechanical modeling of the living body, in particular musculoskeletal modeling (MSM). The all-dominating area of application is of course the human body, but our technology applies to analysis of any creature – currently living, prehistoric, or imaginary. Our base technology is the AnyBody Modeling SystemTM – the simulation engine – and the AnyBody Managed Model Repositories for instance containing the world's most comprehensive human full-body musculoskeletal model.



What do we deliver?

We deliver the AnyBody software, models, assisting tools for a setting up a full simulation tool chain. We also provide simulation consultancy service for your specific R&D purposes, or as support and assistance to your inhouse simulation resources.



Why Musculoskeletal Modeling?

Musculoskeletal modeling is a computational way to investigate the mechanical functions of the living body.

Musculoskeletal models output loading in all muscles, joints, and potentially other tissue of the body, as well as potential derived quantities targeting for instance loading of devices, ergonomic analysis, human performance in sports, and the development of cutting-edge designs. Augment laboratory and field studies with biomechanical analyses and use simulation studies as in-silico evidence of the efficacy and safety of your device.

Simulation can make qualified estimation of properties inside the body,



Thank you for your attention - Time for questions

