PhD in Mechanical Engineering, 33rd Cycle

Modelling the Physical Human-Exoskeleton Interface

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Background

Biomechanical analysis of exoskeletons through musculoskeletal modelling

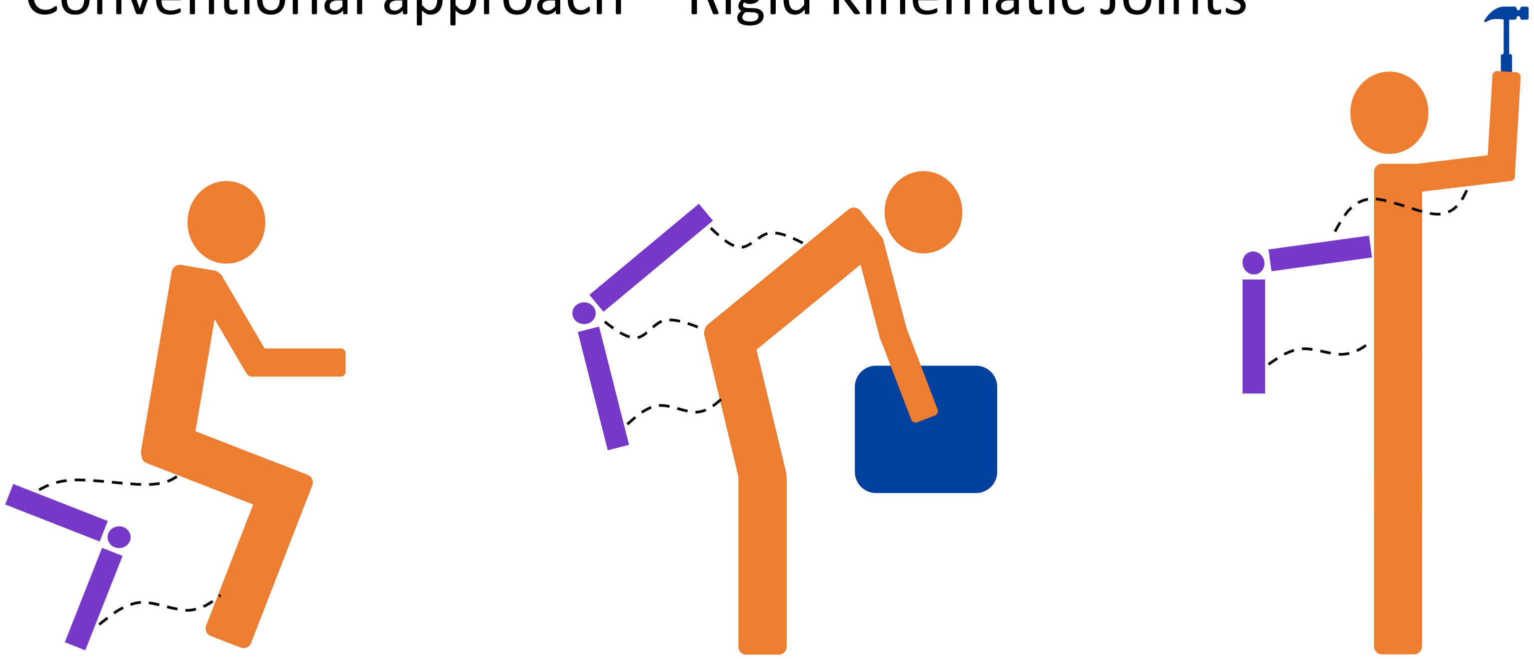
- Estimate internal body loads through virtual models
- Evaluate Pros and Cons objectively

The Problem

Modelling forces at Human-Exoskeleton Interface

- Exoskeletons work by transferring loads
- Correct simulation of interface forces is critical

Conventional approach – Rigid Kinematic Joints



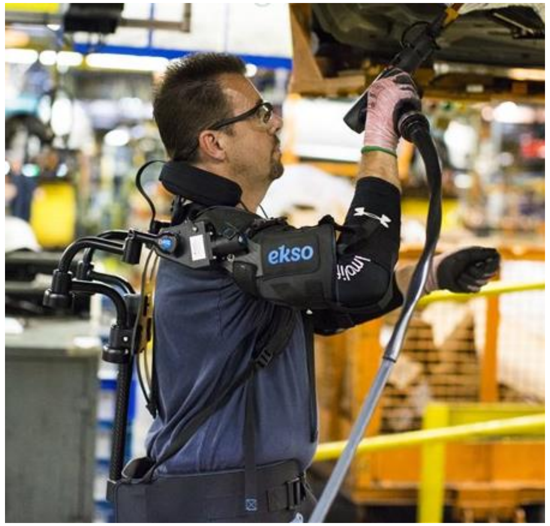
Fix exoskeleton to user
Limitless interface forces

Reality

Contact through straps or molded surfaces

https://www.noonee.com/en/

http://en.laevo.nl/



https://eksobionics.com/

Human-Exoskeleton interaction

- Friction at the interface
- Limited forces – pain/comfort considerations

Aim:

- Develop contact model for human-exoskeleton interaction
- Compare with conventional approach

Outline

- **Aim**: Develop contact model for human-exoskeleton interaction; Compare with conventional approach
- **Methods**: Basics of musculoskeletal modelling; Workflow for biomechanical analysis
- **Year 1**: Simple contact model; Simulate planar surface
- **Year 2**: Advanced contact model; Simulate curved surface
- **Year 3**: Check on second exoskeleton; Simulate multiple interfaces
- **Discussion/ Conclusion**

Year 1 – Year 2: Research collaboration with **FCA - CRF**

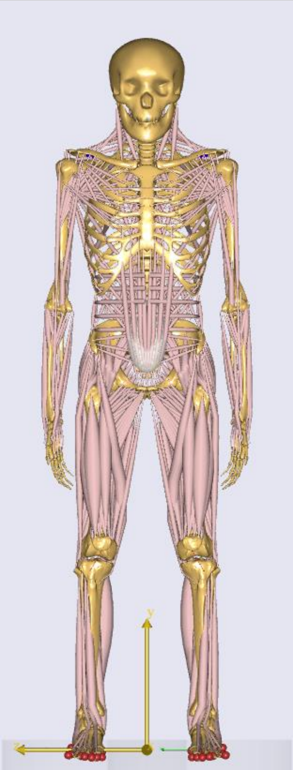
Year 3: 5 month visiting period at **Aalborg University (DK)**; Research cooperation with **HTWK Leipzig (DE)**

Methods

- Musculoskeletal modelling
- Multibody system
- Inverse dynamics analysis

- Human
- Exoskeleton
- Human-Exoskeleton Interaction

INPUT

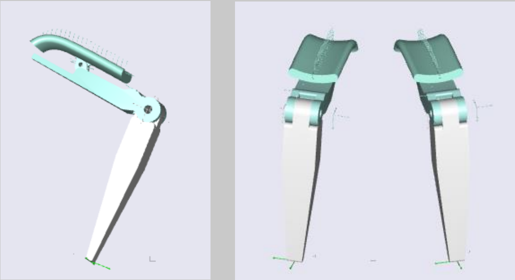


Motion Data
Human
Exoskeleton

+

Force Data
GRF*
Exoskeleton

*Computed if not available

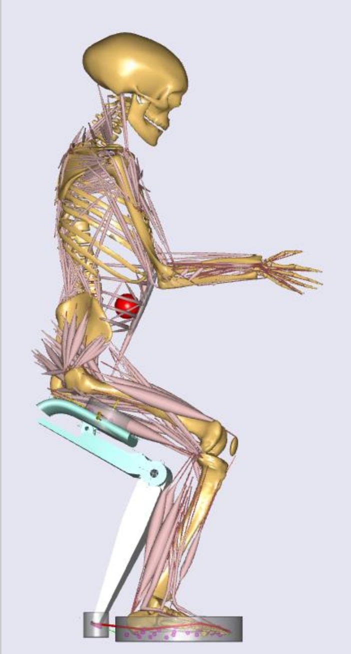


Human Model
40 segments, 85 DOF
> 600 muscle elements

Exoskeleton Model
Import CAD data
Add Force data

Inverse Dynamics

OUTPUT



Internal Body Loads
Muscle forces
Joint moments, reaction forces

AnyBody Modeling System™ & AnyBody Managed Model Repository™

Case Study

Switch between standing/walking and seated posture

Chairless Chair®

https://www.noonee.com/en/

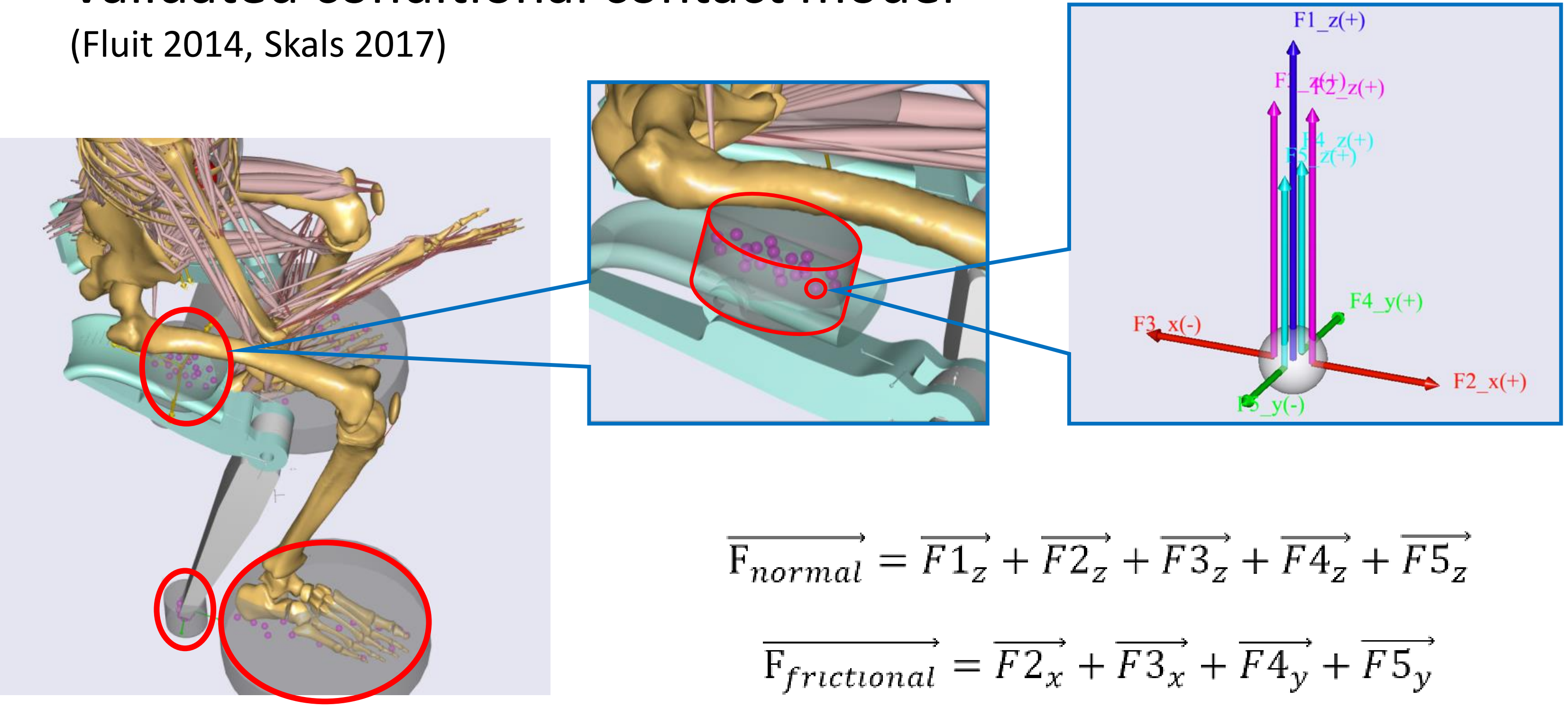
- Passive lower body exoskeleton
- Developed by noonee™ (ETH Zurich spin-off)

Adjustable to user's anthropometry
Adjustable sitting heights

Interface model

Validated conditional contact model

(Fluit 2014, Skals 2017)



Simple Contact Model

- Planar seat surface

$$\overrightarrow{F_{normal}} = \overrightarrow{F1_z} + \overrightarrow{F2_z} + \overrightarrow{F3_z} + \overrightarrow{F4_z} + \overrightarrow{F5_z}$$

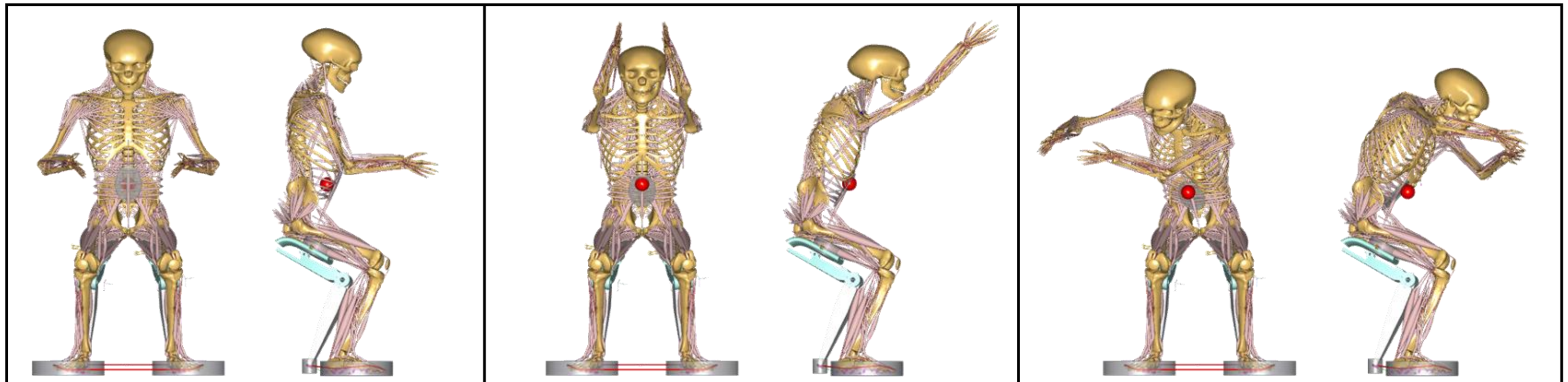
$$\overrightarrow{F_{frictional}} = \overrightarrow{F2_x} + \overrightarrow{F3_x} + \overrightarrow{F4_y} + \overrightarrow{F5_y}$$

- Friction forces
- Maximum force – strength

5 unidirectional force actuators (artificial muscles): 1(normal) + 4(coplanar)

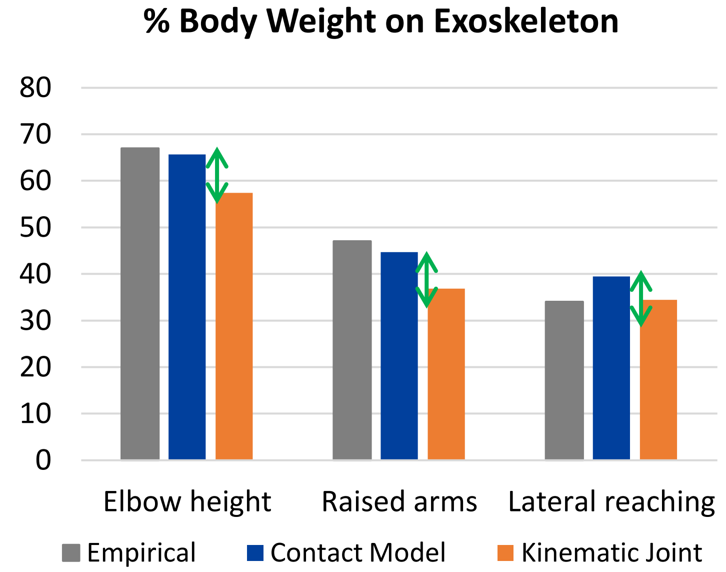
Coefficient of friction: Frictional force = **μ**.(Normal force)

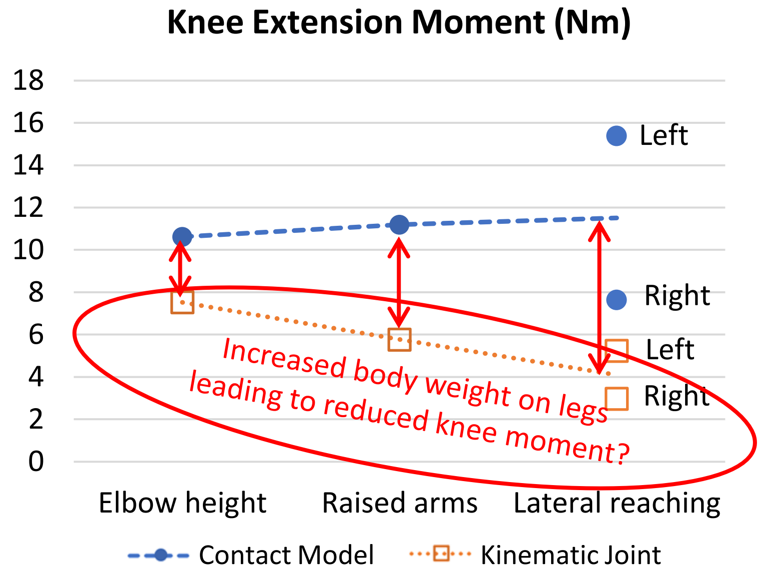
Initial Results



a.) Working at elbow height b.) Reaching with raised arms c.) Lateral reaching (to the right)

Contact model vs rigid kinematic joint model



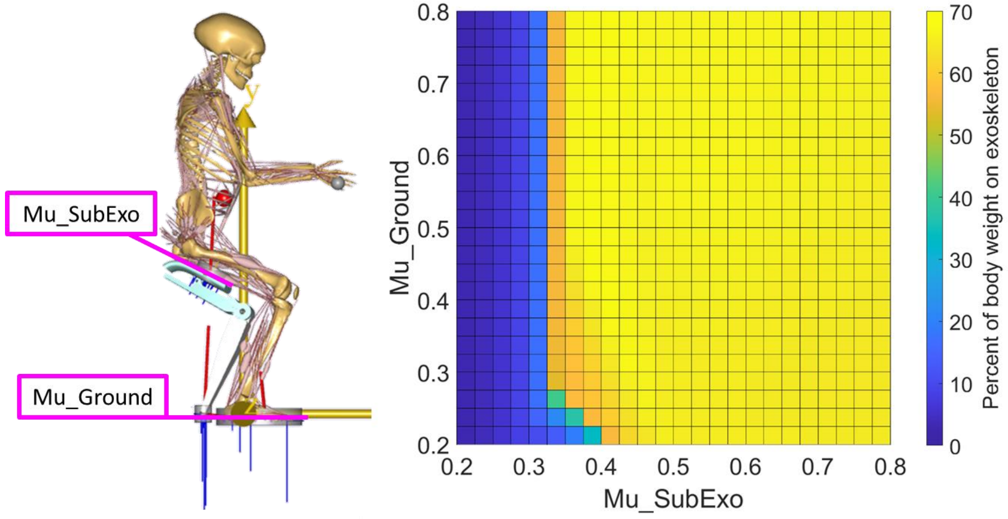


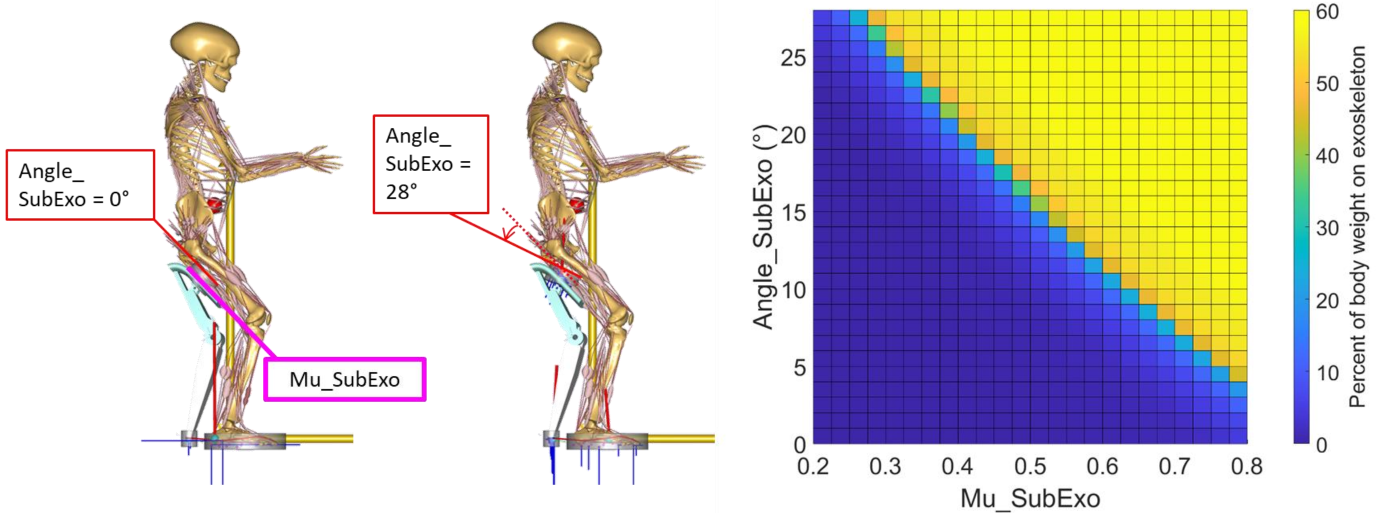
- Similar trends for weight distribution
- Different trends for knee extension moment

Chander, D.S. and Cavatorta, M.P. (2019) 'Modelling friction at the mechanical interface between the human and the exoskeleton', Int. J. Human Factors Modelling and Simulation, Vol. 7, No. 2, pp.119–136

Parametric Studies

- Coefficient of Friction
- Coefficient of Friction and Angle of Seat





Exoskeleton efficiency depends on

- Coefficient of friction at Human-Exoskeleton Interface
- Angle of contact

Chander, D.S. and Cavatorta, M.P. (2019) 'Modelling friction at the mechanical interface between the human and the exoskeleton', Int. J. Human Factors Modelling and Simulation, Vol. 7, No. 2, pp.119–136

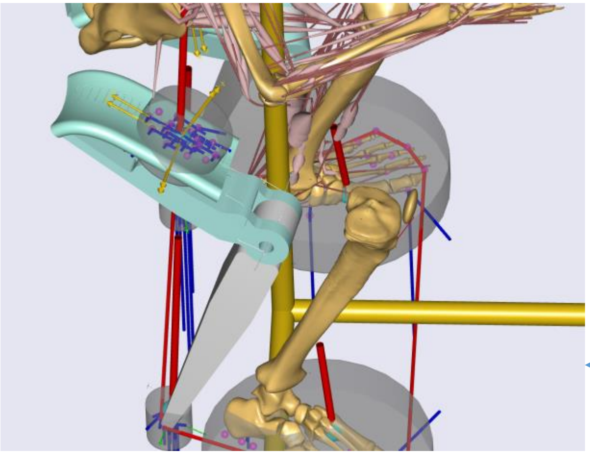
Simulation of curved surface

Simulation of planar seat:

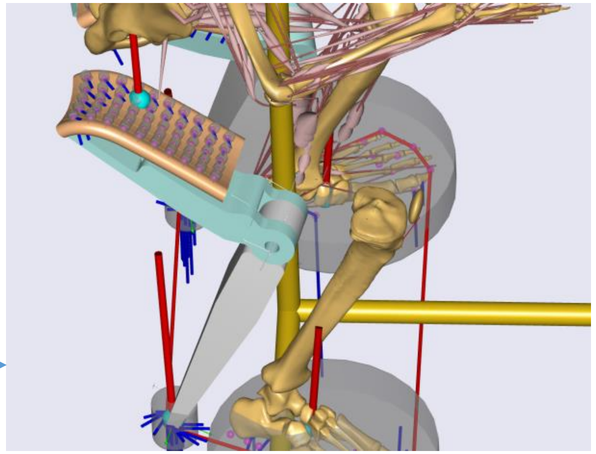
- Location of support
- Orientation of contact

Refining the interface model

- Multiple contact detection zones or Virtual Force Plates (VFPs).
- VFPs are oriented tangential to the seat surface.
- Each VFP has its unique contact node.
- Each VFP could be controlled individually to allow for a realistic contact area.

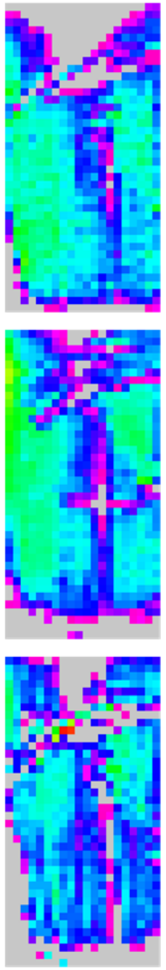


Similar results between the 2 models when there is similar contact area

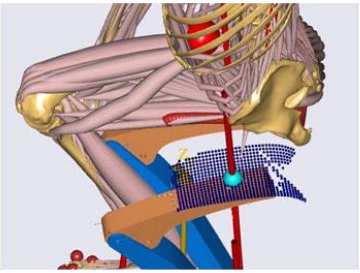


Experiments

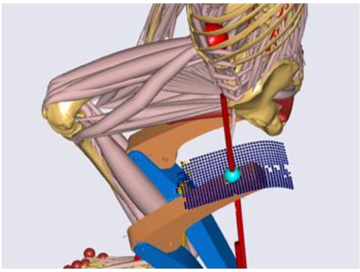
Experimental pressure maps



Low Seat

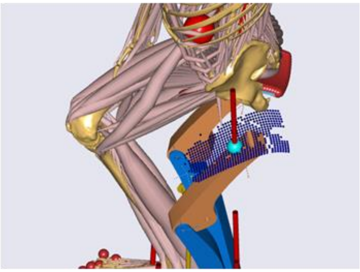


Comfort Seat



$$S_{ij} = \begin{cases} 0.0 & \text{if } P_{ij} = 0.0 \\ S_0 & \text{if } P_{ij} > 0.0 \end{cases}$$

High Seat



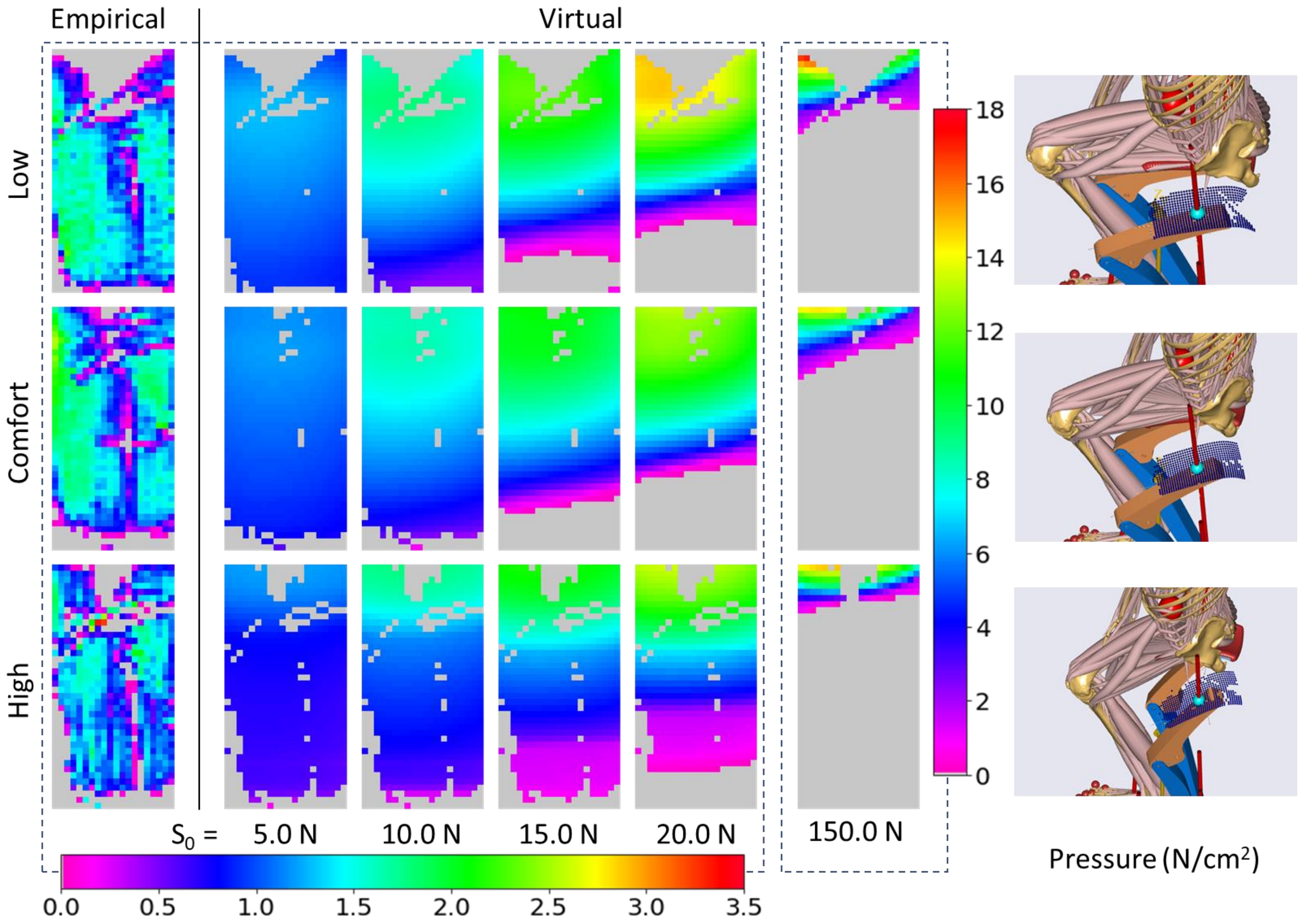
- Centre of pressure
- Area of contact
- Weight distribution

Identify contact area at Exoskeleton seat using pressure mat (Xsensor).
Use empirical data to control presence of VFPs in the model.

Results

Virtual pressure maps

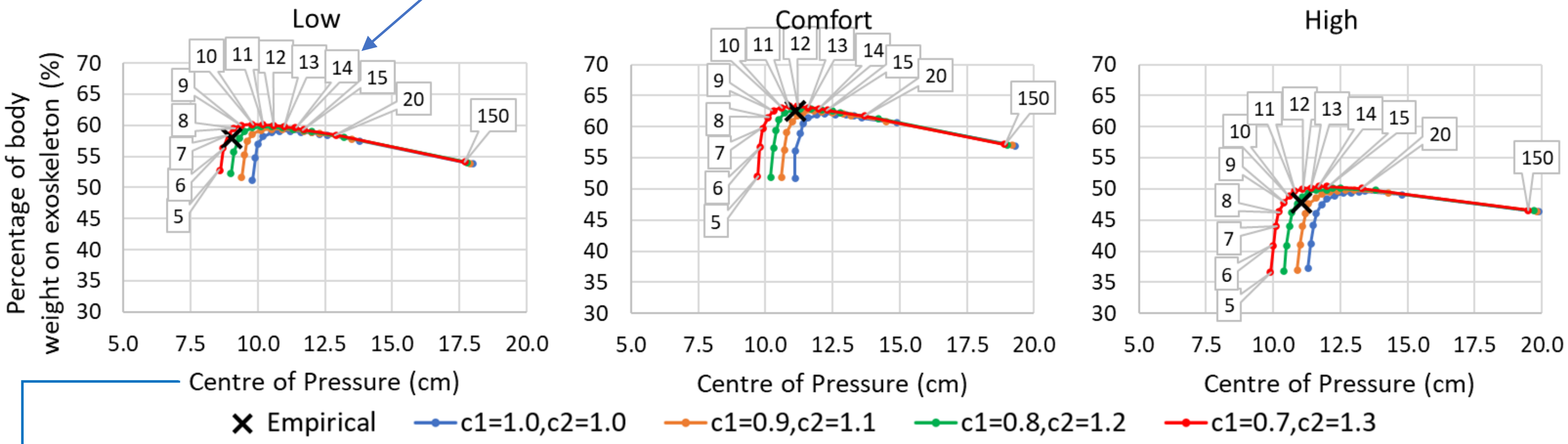
Preference of solver for the rear portion of the seat

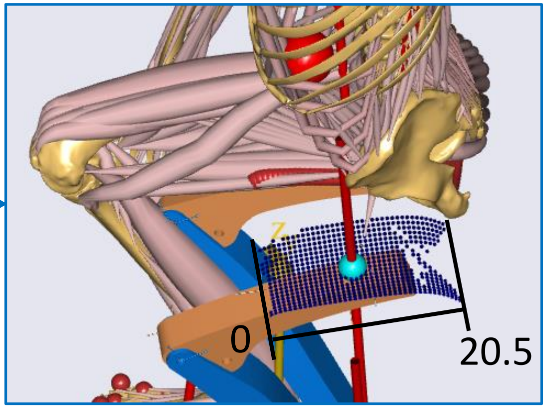


Results

$$S_{ij} = \begin{cases} 0.0 & \text{if } P_{ij} = 0.0 \\ S_0 \times [c_1 + (i-1) \times (c_2 - c_1)/39] & \text{if } P_{ij} > 0.0 \end{cases}$$

% weight on Exoskeleton vs Centre of Pressure (COP)





- Indication of zone of optimal strength of contact muscles

Optimal strength: Correct compromise % weight transfer and CoP location

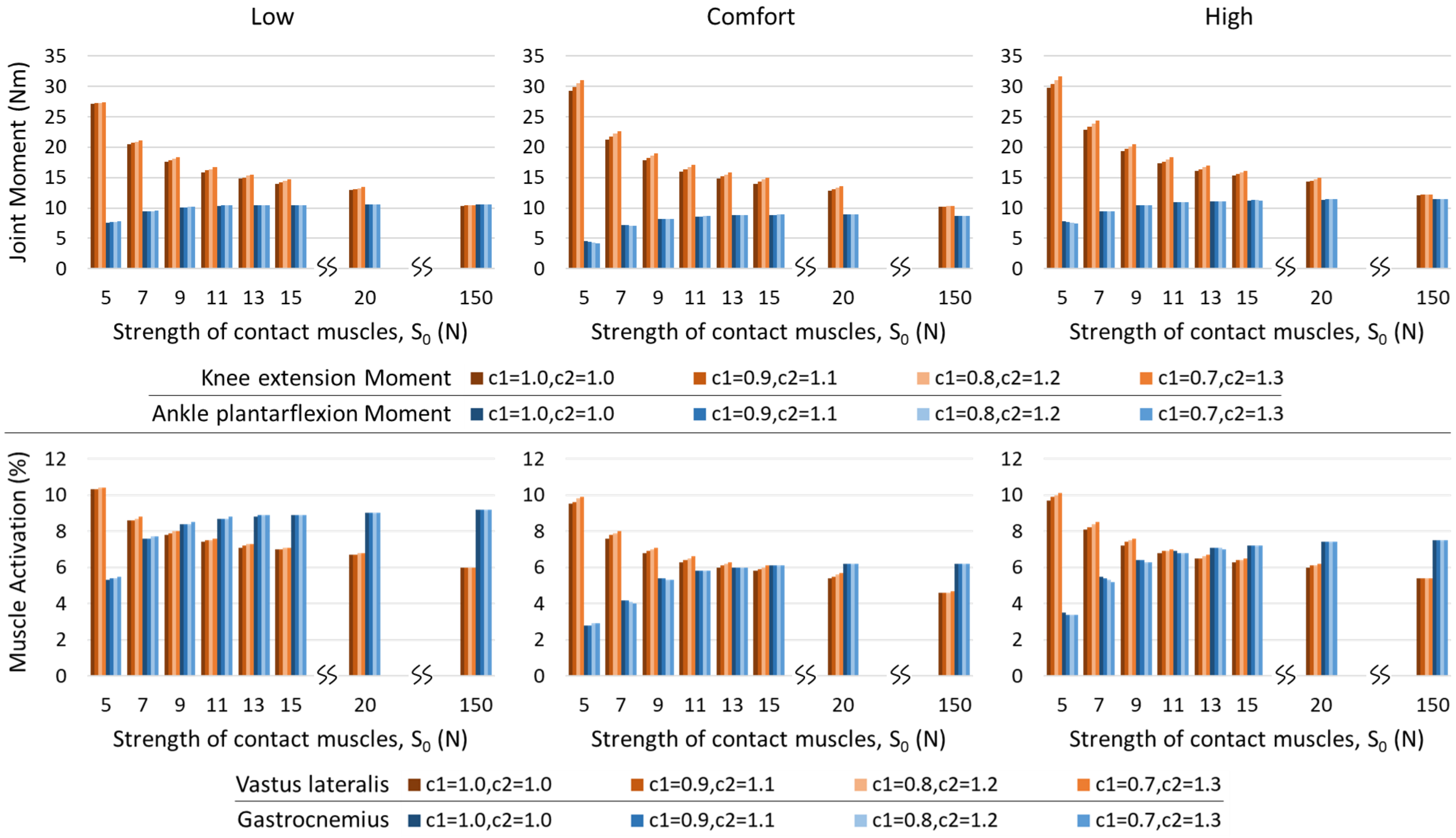
Excess strength: Weight transfer in a limited zone

Insufficient strength: Limited weight transfer

Results

Biomechanical outputs vs strength of interface muscles

- Biomechanical outputs depend on the strength of the interface muscles

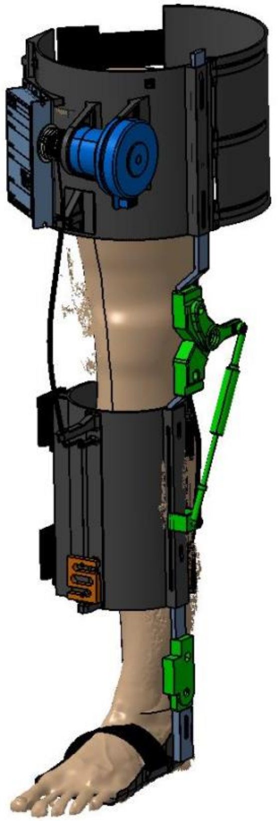


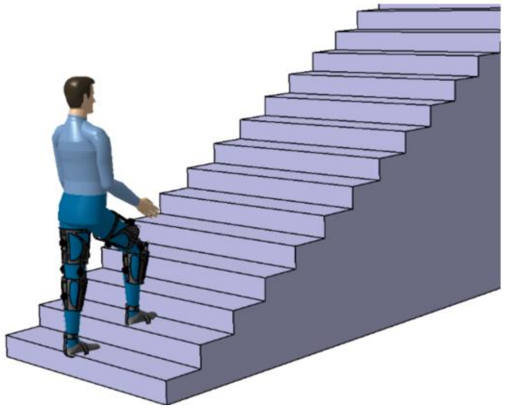
Chander, D.S. and Cavatorta, M.P. (2020) 'Modelling Interaction Forces at a Curved Physical Human-Exoskeleton Interface', Proceedings of the 6th International Digital Human Modeling Symposium (DHM2020), pp 217 - 226.

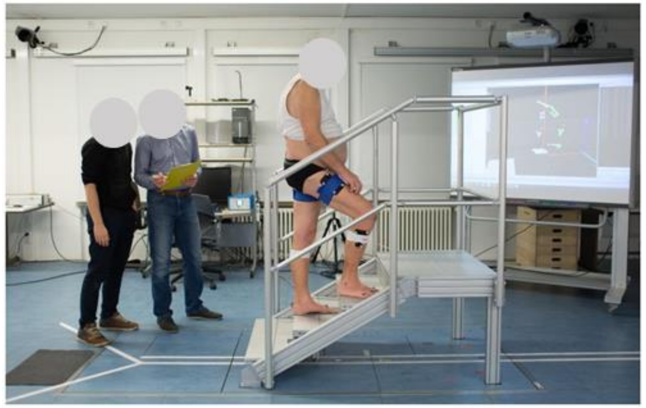
Case Study 2

DEMOS – Development of minimal actuated movement support systems

Modelling of a generic interface







Project Goal: Stair negotiation for the ELDERLY
Exoskeleton in development at **HTWK Leipzig**

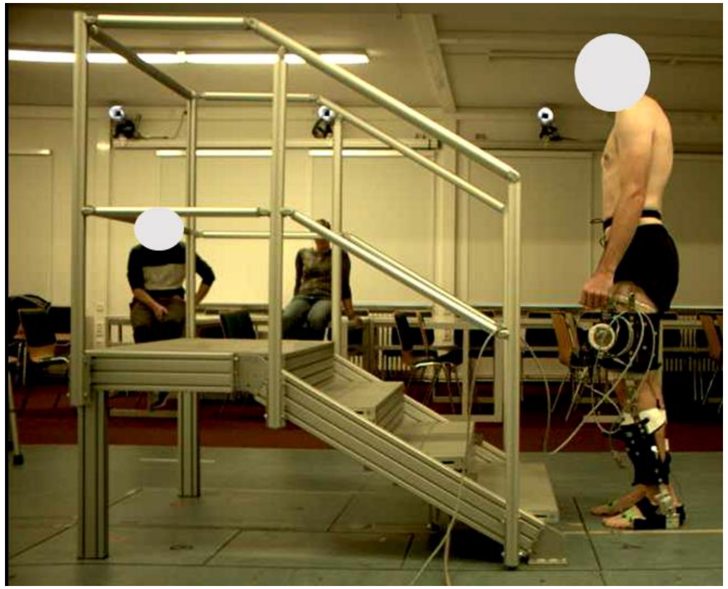
Musculoskeletal modeling cooperation between:
HTWK Leipzig, **Politecnico di Torino**, and **Aalborg University**.

Characteristics of Chairless Chair:

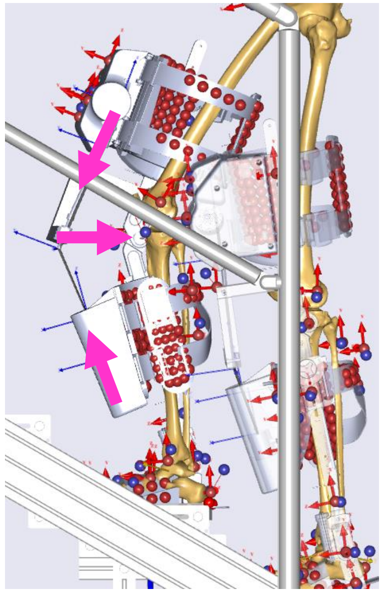
- Single interface that supports from one side
- Static assistance

https://demos.htwk-leipzig.de/, https://www.biomechanics.mp.aau.dk/

Experiments

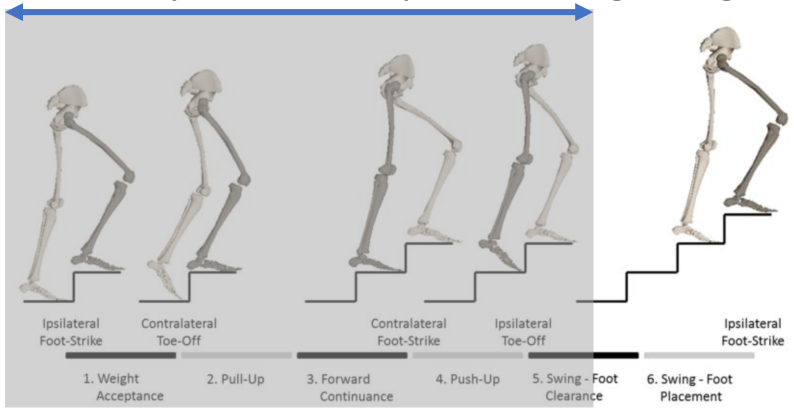


- Stair ascent
- Assistance: Active cable drive for knee extension



Markers on human and exoskeleton.
Relative movement between human and exoskeleton

Analysis: Stance phase of right leg



1 subject
8 trials

Source: Harper (2018) Muscle function and coordination of stair ascent

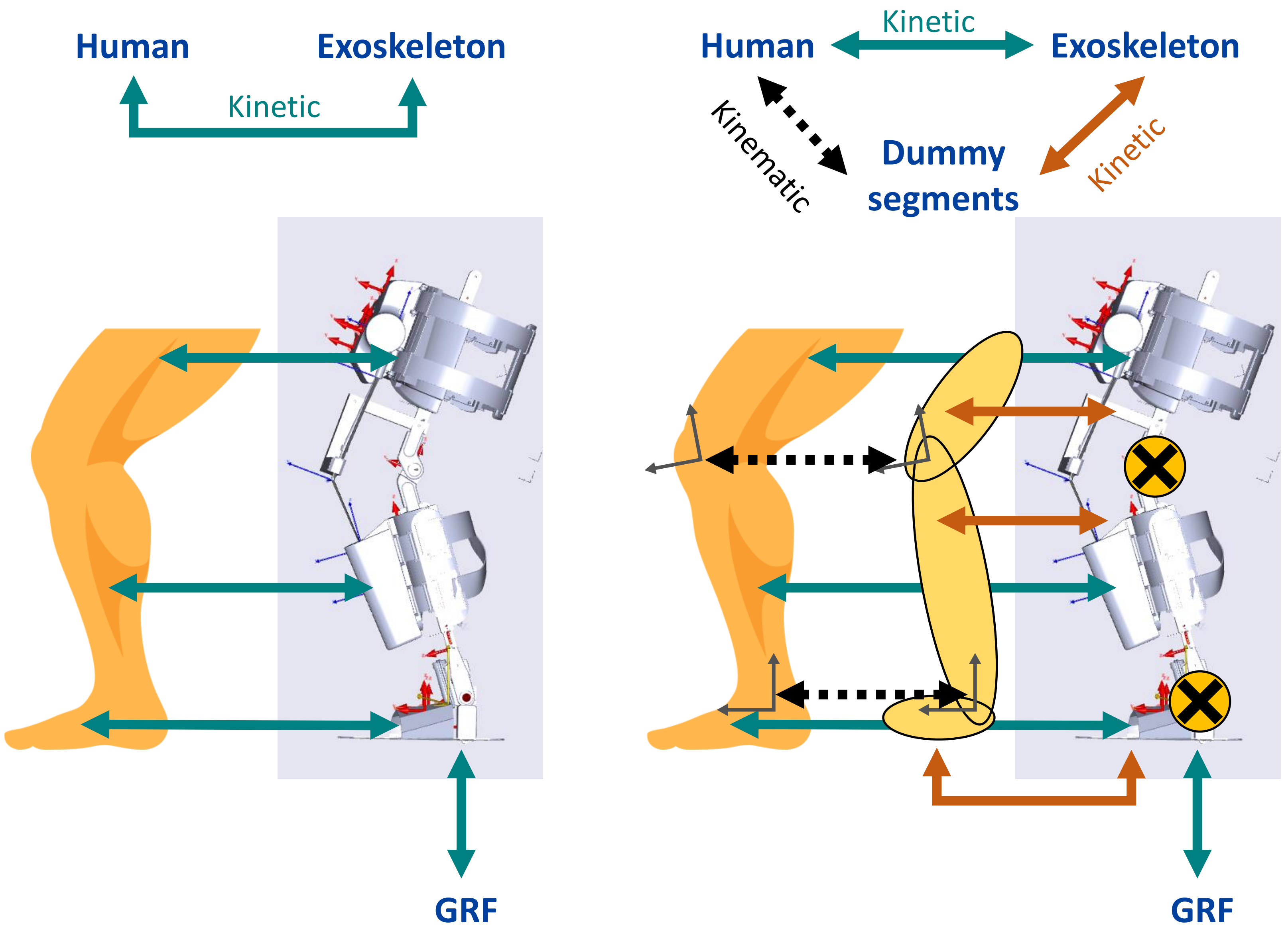
- Mocap + GRF
- Actuator force
- EMG

Interface modelling

- Misalignment between human and exoskeleton
- Unloading of physiological muscles

Dummy Segments:

- Mass-less, inertia-less
- Align exoskeleton joints with human joints



Interface models

Kinetics:

- Contact model (DS)
- Kinematic joint
- Redundant reactions (DS)

Kinematics:

- Marker-driven exoskeleton
- Kin. joint driven exoskeleton

	Contact Model	Kinematic Joints	Dummy Segments	Redundant Reactions
CMDS	x		x	
KJ		x		
KJDS		x	x	
CMKJDS	x	x (kinematics only)	x	
RRDS			x	x
KJRRDS		x	x	x

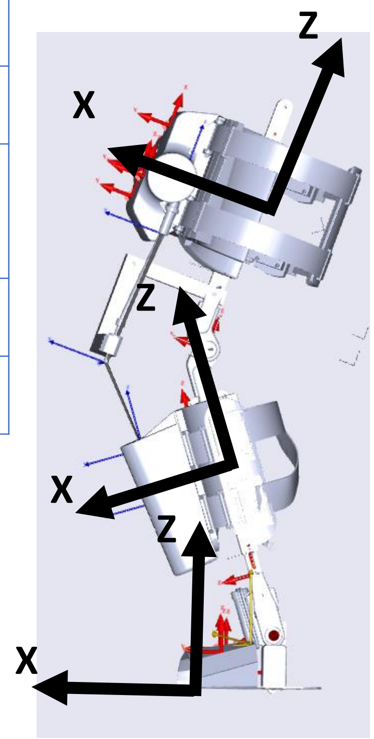
8 Extra Constraints = 8 Extra DOF of exoskeleton

One possible combination:

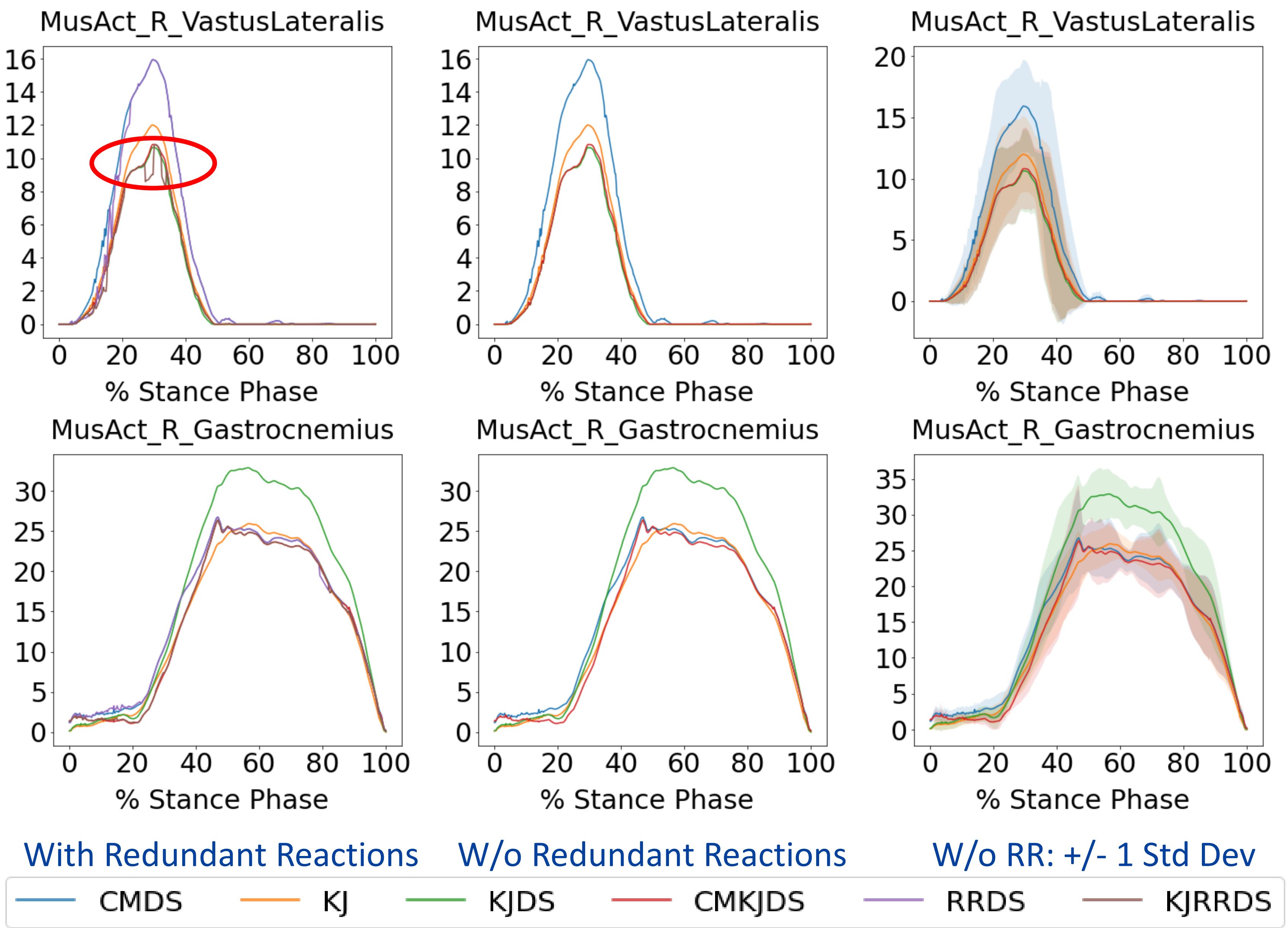
Thigh (3): Trans(x,y); Rot(z)

Shank (4): Trans(x,y,z); Rot(y)

Foot (1): Trans(z); Rot()



Results



Muscle Activation (%)

- Vastus Lateralis
- Gastrocnemius

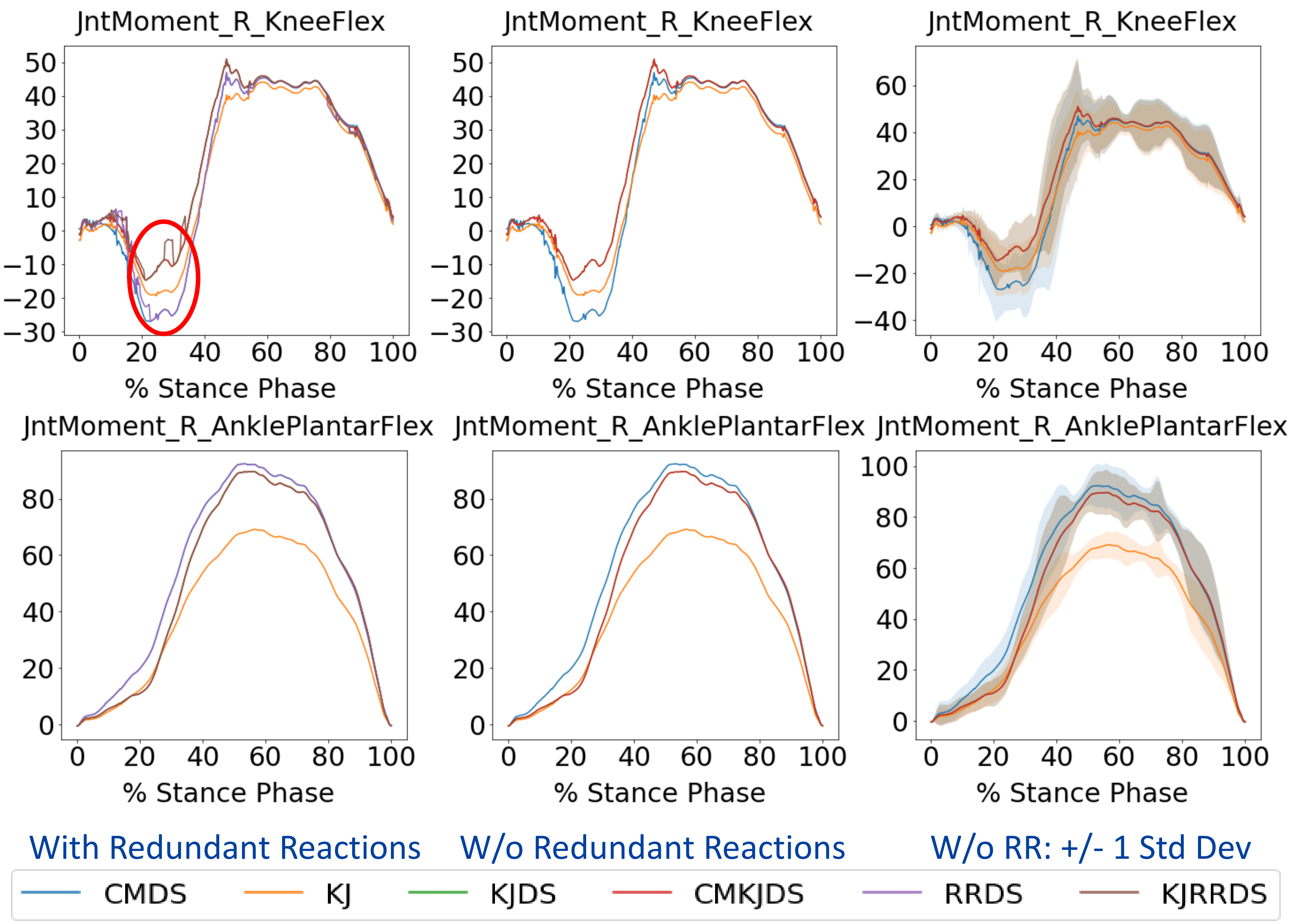
- RR shows fluctuations
- Slight difference vastus lateralis
- KJDS higher in gastrocnemius

Results

Joint moment (Nm)

- Knee flexion
- Ankle plantarflexion

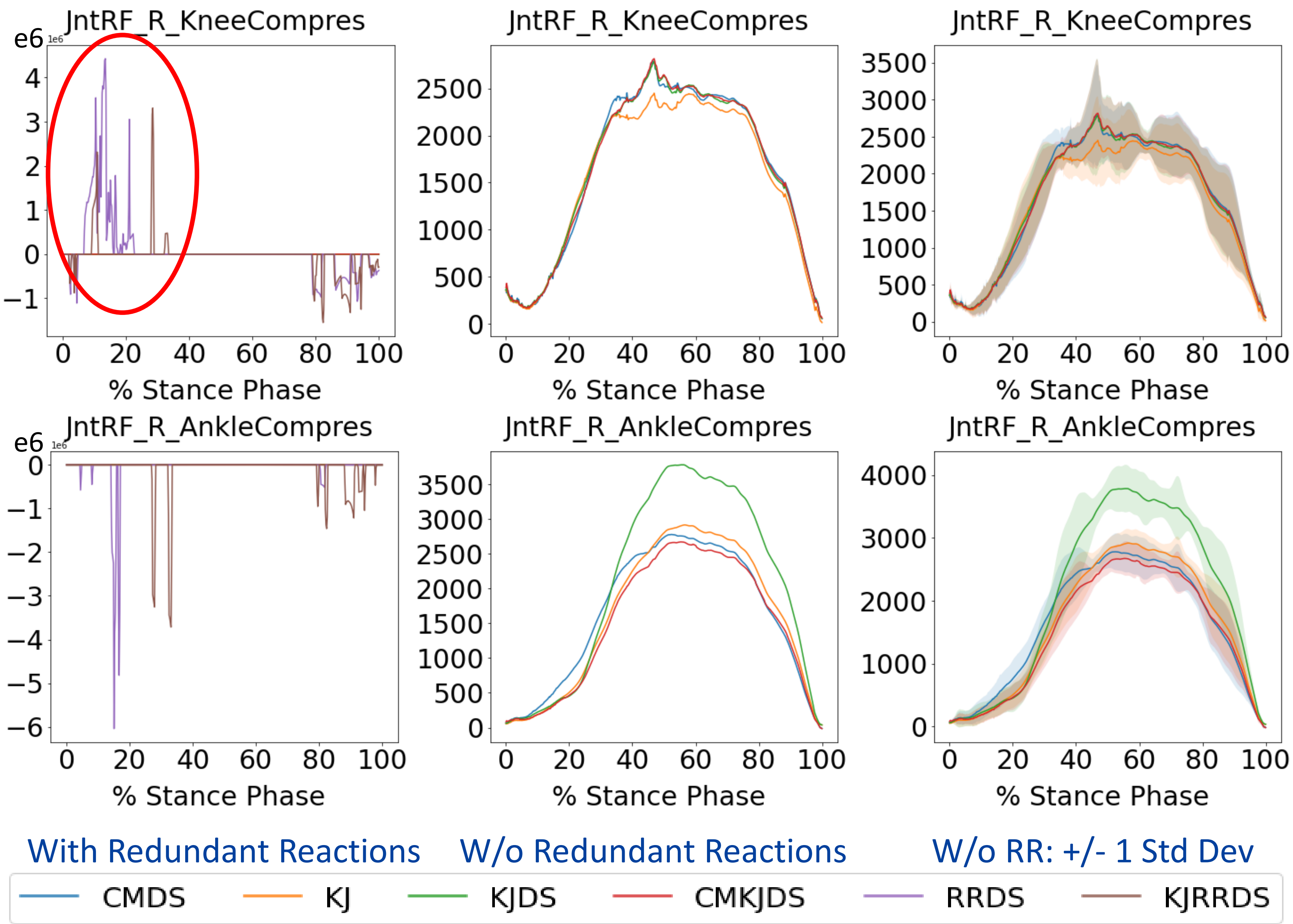
- RR shows fluctuations
- Similar results about knee
- KJ lower about ankle



Results

Joint reaction forces (N)

- Knee compression
- Ankle compression



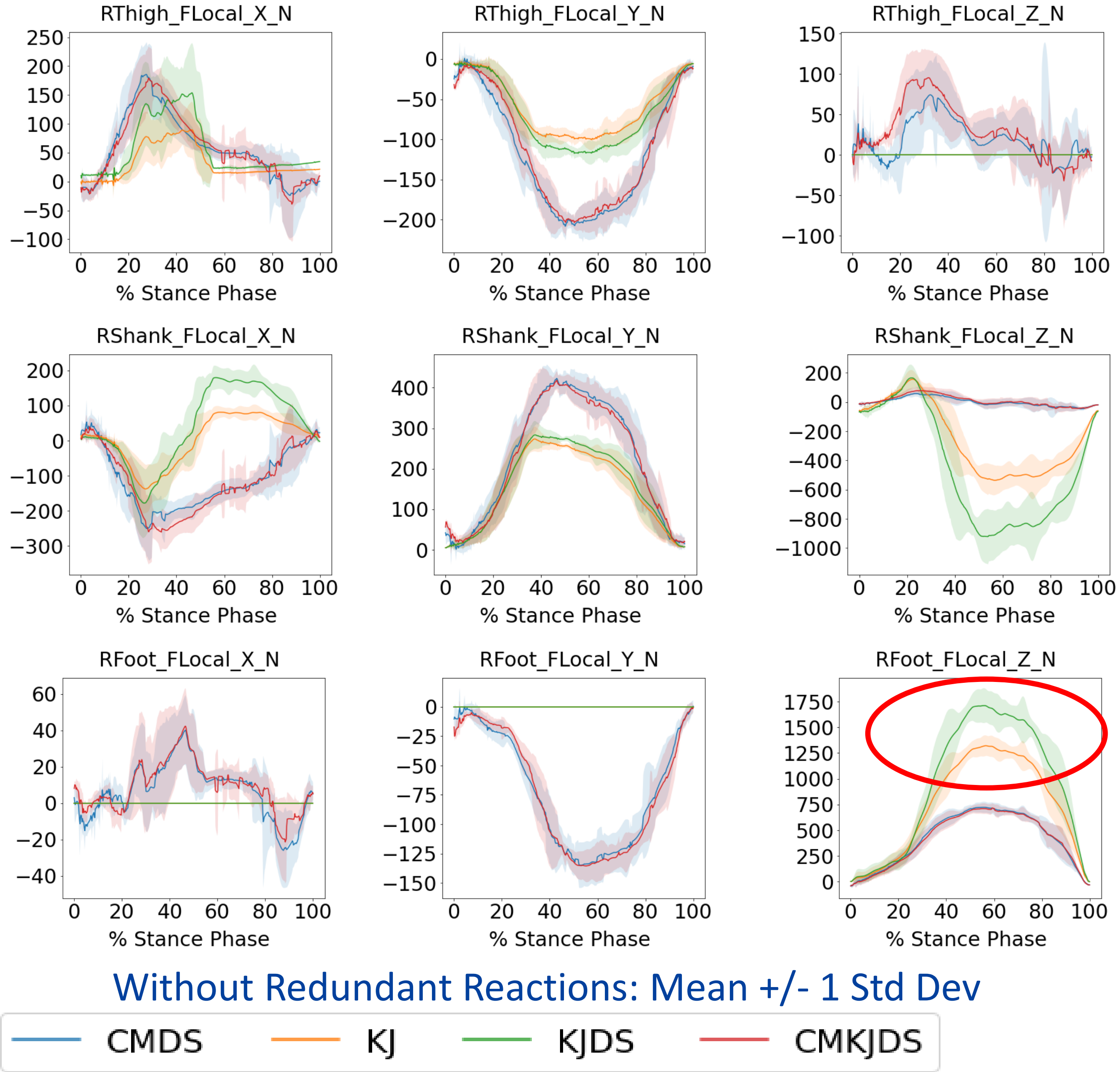
- RR shows excessive values
- Similar results at knee
- KJDS higher at ankle

Results

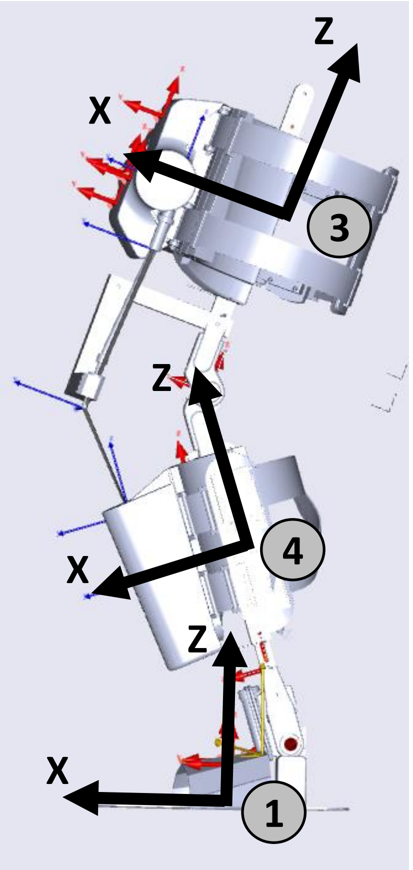
Interface forces (N)

- Thigh, shank, foot
- Fx, Fy, Fz

- KJ/KJDS have limited reactions – excessive force at foot
- CMDS/CMKJDS provide all reactions



Without Redundant Reactions: Mean +/- 1 Std Dev



(n) no. of kinematic constraints in KJ models

Discussion

- RR shows excessive fluctuations in outputs
- Comparison of 4 models only

CM: Contact Model KJ: Kinematic Joint DS: Dummy Segments

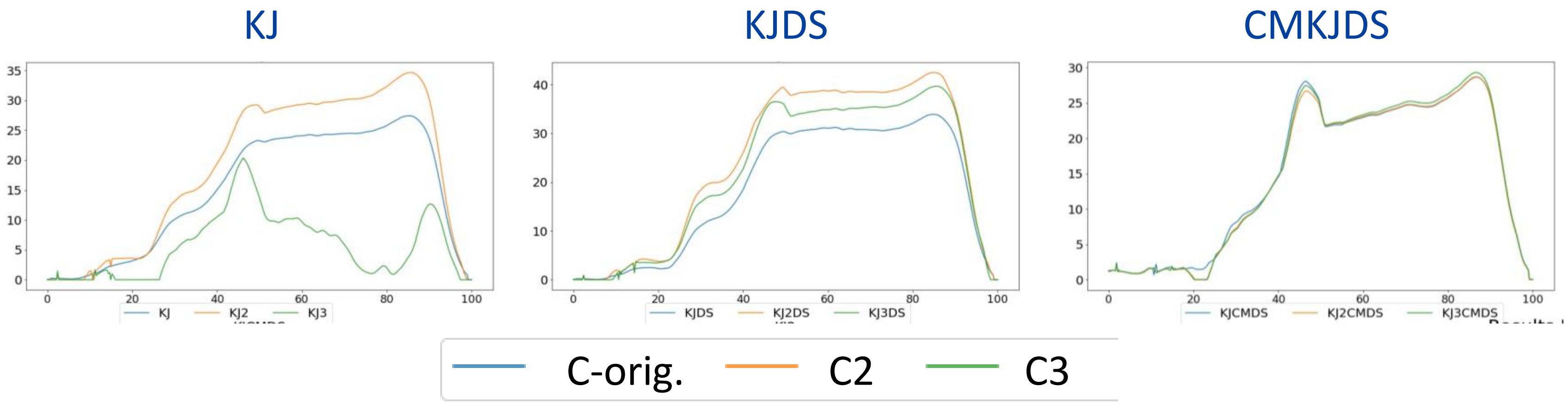
Biomechanical outputs:

- Consistent results about knee:
- Inconsistent results about ankle (KJDS > KJ)

Interface outputs:

- KJ & KJDS have only 1 reaction force at foot – Excessive loading (KJDS > KJ)
  - Changing distribution of constraints changes interface and biomechanical outputs

BioMech_MusAct_R_Gastrocnemius



Conclusions

Conventional approach: Kinematic Joints

- Insufficient interface outputs
- Biomechanical outputs depends on the joint configurations

Contribution: New Contact Model

- Detailed interface outputs, including pressure
- Consistent biomechanical outputs
- Tested on 2 largely different exoskeletons

- Comprehensive comparison of different interface model

THANK YOU!

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Politecnico di Torino

References:
Fluit R, Andersen MS, Kolk S, Verdonschot N, Koopman HFJM. Prediction of ground reaction forces and moments during various activities of daily living. J Biomech Elsevier, 2014, 47(10), 2321–2329.
Skals S, Jung MK, Damsgaard M, Andersen MS. Prediction of ground reaction forces and moments during sports-related movements. Multibody Syst Dyn Springer Science+Business Media Dordrecht,2017, 39(3), 175–195.

Training

Internal Courses:

- Hard skills (4 – 97 hours)
- Soft skills (8 – 58 hours)

External Courses:

- Hard skills (2 – 60 hours)

External research activities:

- 5 months at Aalborg University (DK)

Internal Courses:

Cod Ins.	Nome insegnamento	Ore	Ore riconosciute	Voto	Coeff. voto	Data esame	Tipo form.	Liv. Esame	Tipo attività	Punti
02PILLZ	Lingua italiana IV livello	0	0.00		1.33	18/6/2019	Hard	1	ESAME POLI	0.00
01SWPRO	Time management	2	2.00		1.33	22/7/2019	Soft	3	ESAME POLI	2.67
01UNVRO	Navigating the hiring process: CV, tests, interview	2	2.00		1.33	21/7/2020	Soft	3	ESAME POLI	2.67
01SHMRO	Entrepreneurial Finance	5	5.00		1.33	5/5/2020	Soft	3	ESAME POLI	6.67
08IXTRO	Project management	5	5.00				Soft	3	ESAME POLI	
02LWHRO	Communication	5	5.00		1.33	4/9/2018	Soft	3	ESAME POLI	6.67
01RISRO	Public speaking	5	5.00		1.33	31/8/2018	Soft	3	ESAME POLI	6.67
01SYBRO	Research integrity	5	5.00				Soft	3	ESAME POLI	
01RNCRO	Public Speaking II	12	12.00		1.33	3/5/2019	Soft	3	ESAME POLI	16.00
01RNBRO	Communication II	12	12.00		1.33	3/5/2019	Soft	3	ESAME POLI	16.00
01QORRO	Writing Scientific Papers in English	15	15.00		1.33	21/3/2018	Soft	3	ESAME POLI	20.00
01UKCRO	3D motion tracking in body mechanics	15	15.00				Hard	3	ESAME POLI	
04QDBRP	Metodi statistici nei processi di progettazione, produzione e verifica	20	20.00				Hard	3	ESAME POLI	
01RONKG	Python in the Lab	20	20.00				Hard	3	ESAME POLI	
01QTEIU	Data mining concepts and algorithms	20	20.00		1.67	14/12/2018	Hard	3	ESAME POLI	33.33
02QUBRS	Statistical data processing	20	20.00				Hard	3	ESAME POLI	
01TAFRP	Pianificazione degli esperimenti industriali	24	24.00		1.67	11/7/2019	Hard	3	ESAME POLI	40.00
01LEXRP	Strumenti e tecnologie per lo sviluppo del prodotto	25	25.00		1.67	7/6/2018	Hard	3	ESAME POLI	41.67
01RQFRO	Progettazione affidabilistica di macchine e sistemi meccanici	28	28.00		1.67	6/11/2019	Hard	3	ESAME POLI	46.67
		Ore Soft Skills	**58.00**						**Punti Soft Skills**	**77.33**
		Ore Hard Skills	**97.00**						**Punti Hard Skills**	**161.67**
		Ore totali	**155.00**						**Punti totali**	**239.00**

External Courses:

Denominazione	Ore	Coeff. voto	Tipo form.	Tipo Richiesta	Liv. Esame	Data attività	Data convalida	
PhD course on "Advanced Musculoskeletal Modeling with Emphasis on Exoskeletons and IMU Drivers& […]	30	1.00	Hard	Consuntiva	3	18/3/2019	3/6/2019	Dettagli
PhD course on "Advanced Musculoskeletal Modeling"	30	1.00	Hard	Consuntiva	3	30/4/2018	24/7/2018	Dettagli
Ore Convalidate	**60**	**Punti Convalidati**	**60.00**					

External research activities:

Denominazione	Luogo	Ente	Periodo	Data autorizzazione	Data attestaz.	Data convalida	
Visiting PhD Aalborg University	DANIMARCA - Aalborg	Aalborg University	1/2/2020 - 30/6/2020	16/12/2019	15/7/2020	16/7/2020	Dettagli

Publications

- 3: International journal
- 2: Conferences

- 1: In preparation (International journal)

Anno	Tipo	Titolo	Rivista	Autori	Convegno	Referee	Grado proprietà dottorandi	Punteggio	Grado proprietà	Indicatore R	Errore Val.
2017	1.1 Articolo in rivista	An observational method for Postural Ergonomic Risk Assessment (PERA)	INTERNATIONAL JOURNAL OF INDUSTRIAL ERGONOMICS	Chander, Divyaksh Subhash; Cavatorta, Maria Pia		1	1	1	0.707107	57.07	
2018	1.1 Articolo in rivista	Multi-directional one-handed strength assessments using AnyBody Modeling Systems	APPLIED ERGONOMICS	Chander, Divyaksh Subhash; Cavatorta, Maria Pia		1	1	1	0.707107	57.07	
2019	4.1 Contributo in Atti di convegno	Physical and Virtual Assessment of a Passive Exoskeleton		Spada, Stefania; Ghibaudo, Lidia; Carnazzo, Chiara; Di Pardo, Massimo; Chander, DIVYAKSH SUBHASH; Gastaldi, Laura; Cavatorta, MARIA PIA	20th Congress of the International Ergonomics Association, IEA 2018	1	1	0.5	0.188638	0.94	
2019	1.1 Articolo in rivista	Modelling friction at the mechanical interface between the human and the exoskeleton	INTERNATIONAL JOURNAL OF HUMAN FACTORS MODELLING AND SIMULATION	Chander, Divyaksh Subhash; Cavatorta, Maria Pia		1	1	0	0.707107	50.00	Rivista non valutata o nel quarto quartile
2020	4.1 Contributo in Atti di convegno	Modelling interaction forces at a curved physical human-exoskeleton interface		Chander, D. S.; Cavatorta, M. P.	6th International Digital Human Modeling Symposium, DHM 2020	1	1	0.5	0.707107	3.54	