DigitalExonomics Musculoskeletal Exoskeleton Assessment with AnyBody™

Fraunhofer

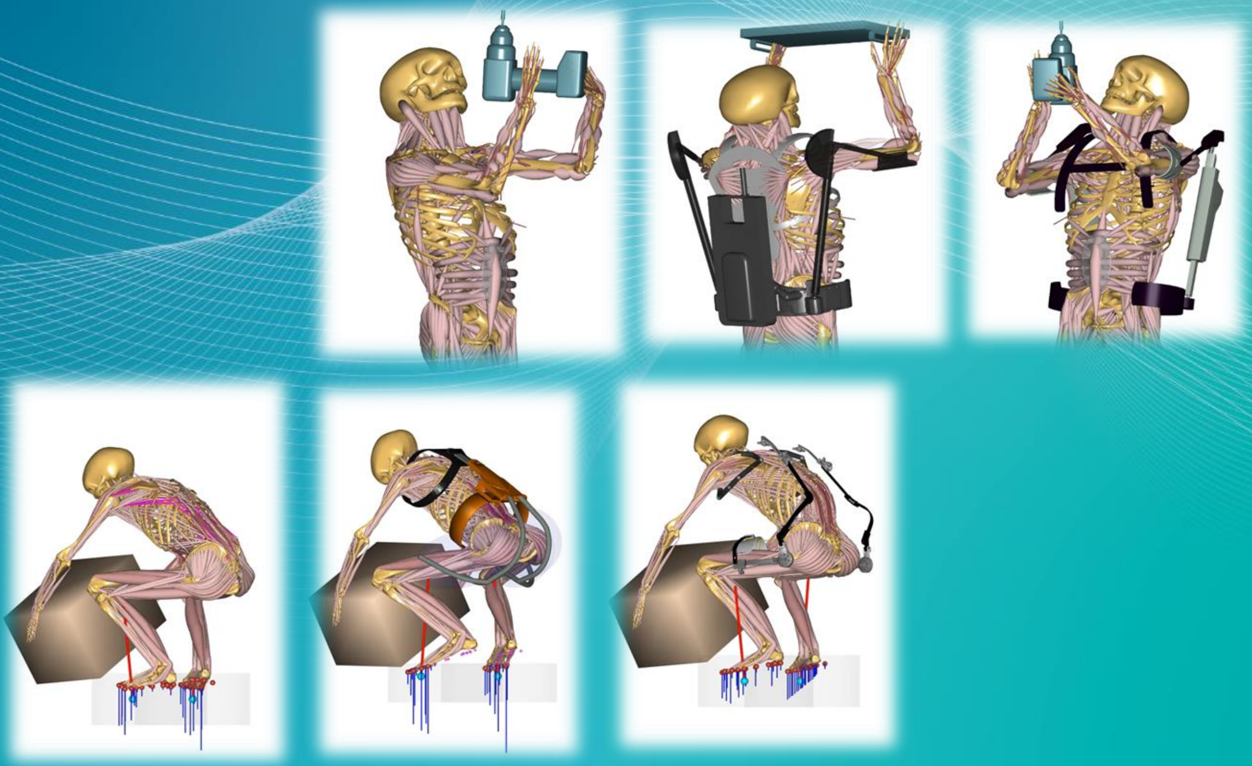
IPA

Fraunhofer Institute for Manufacturing Engineering and Automation IPA

University of Stuttgart
Institute of Industrial Manufacturing and Management IFF

Fraunhofer IPA
Healthcare Technologies and Processes
&
University of Stuttgart, IFF
Human-Technology Interaction

M.Sc. Urban Daub
Dr.-Ing. Mark Tröster



Fraunhofer-Gesellschaft

Research and create innovations

More than
30 000
employees

In 2021, the hiring rate for female scientists increased to 29 percent (overall, about 23 percent female scientific staff).

More than
75
institutes

2
patent applications per working day

90 %
of our institute directors have a department chair

They combine university research with applied research and development at Fraunhofer.

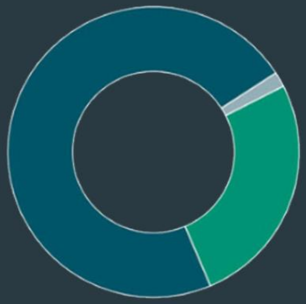
approx.
30
spin-offs per year

... over 500 since the year 2000. Approximately 80 percent are still on the market after ten years.

More than
7600
activ patent families

Fraunhofer is an EU-wide leader in setting standards.

approx. **72.1 %**
wissenschaftliches, technisches und administratives Personal



approx. **1.7 %**
trainees

approx. **26.2 %**
students

Fraunhofer is both an attractive employer and a career springboard.

3.0 billion
euros revenue per year from contract research

Demand from business and society guides growth.

Source: Fraunhofer-Gesellschaft

Fraunhofer IPA at Fraunhofer Institute Centre Stuttgart

Strong partner for different industries

At a glance

- Over 1,000 projects with industrial customers each year
- Approx. 1,200 employees at 9 locations (headquarter: Stuttgart)

- 28 patents granted in 2023
  (10 in Germany, 18 internationally)
- 835 publications in 2023

- Key figures in 2023 in € million 1)
  - Total budget: 94
  - Operating budget: 89 2)
  - Investment budget: 5
  - Industrial revenues: 26

- **Close cooperation with S-TEC and University of Stuttgart | Technology and Innovation Campus**

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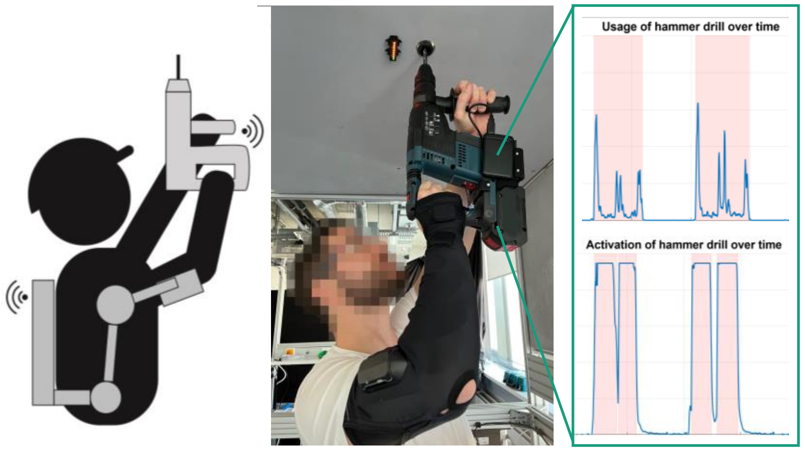
University of Stuttgart, IFF

Research Unit | Human-Technology Interaction

University of Stuttgart
Institute of Industrial Manufacturing
and Management IFF

Physical Assistance Systems

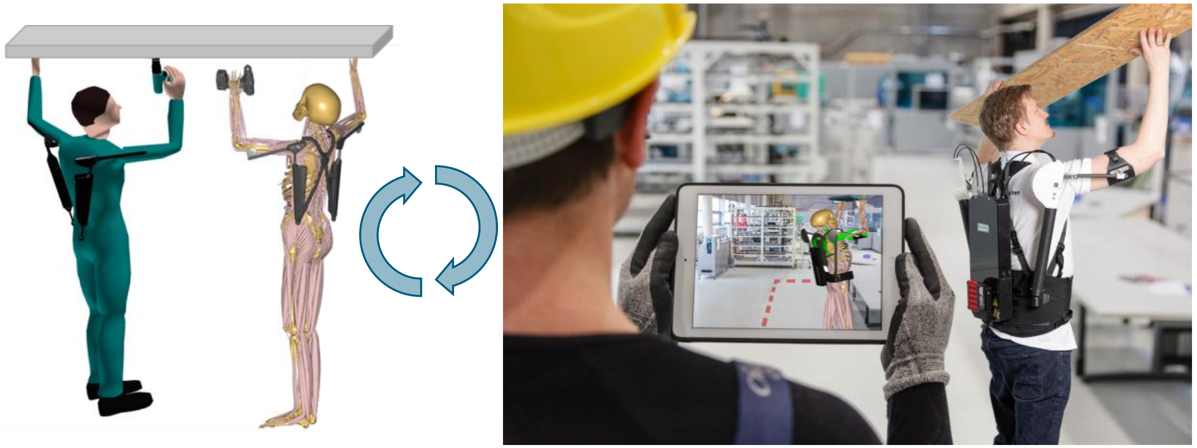
Research for smart body-worn assistance to maintain, restore or increase human mobility



Digital Human Modeling and Ergonomics

Ergonomic (Exoskeleton) Assessment

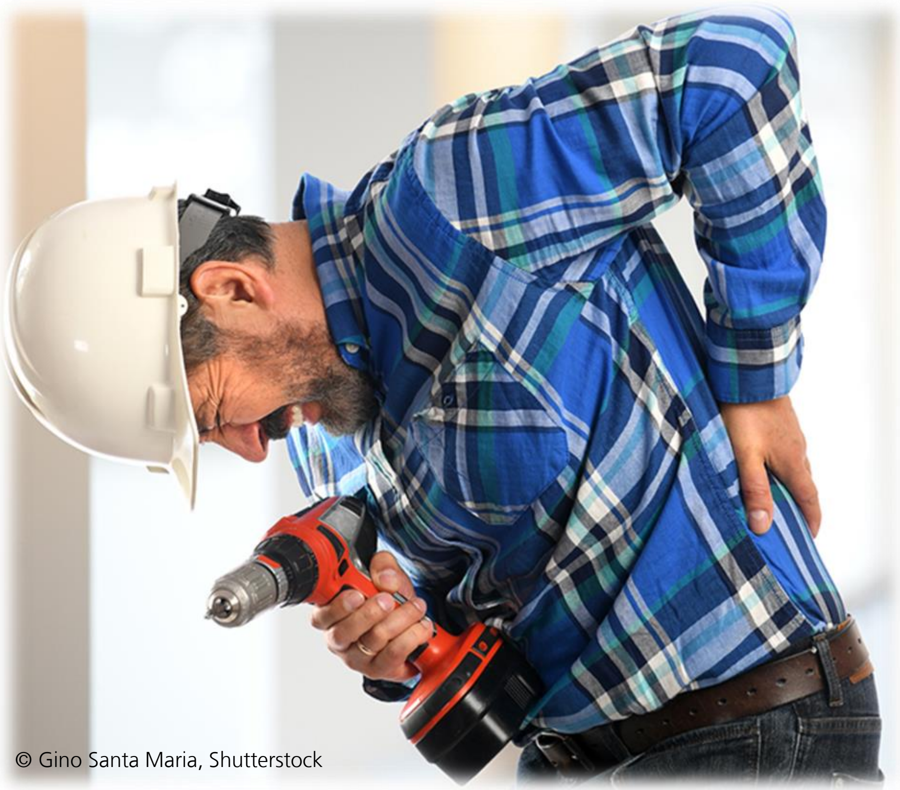
Digital | Personalized | Realtime



Musculoskeletal Disorders in heavy physical work

Better understanding of MSD-etiologies and the effects of ergonomic interventions

World Health Organization



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Musculoskeletal conditions are the leading contributor to disability worldwide, with **low back pain being the single leading cause of disability in 160 countries**.

Musculoskeletal conditions significantly limit **mobility** and **dexterity**, leading to **early retirement from work**, lower levels of well-being and reduced ability to participate in society.

Because of **population growth and ageing**, the **number** of people living with musculoskeletal conditions and associated functional limitations, is rapidly **increasing**.

https://www.who.int/news-room/fact-sheets/detail/musculoskeletal-conditions, accessed on 01/10/2024

Effective relief measures for heavy physical work

Our methodolgical background

The better the cause of frequently occurring complaints is known, the better effective and accepted ergonomic measures can be derived.

Data acquisition

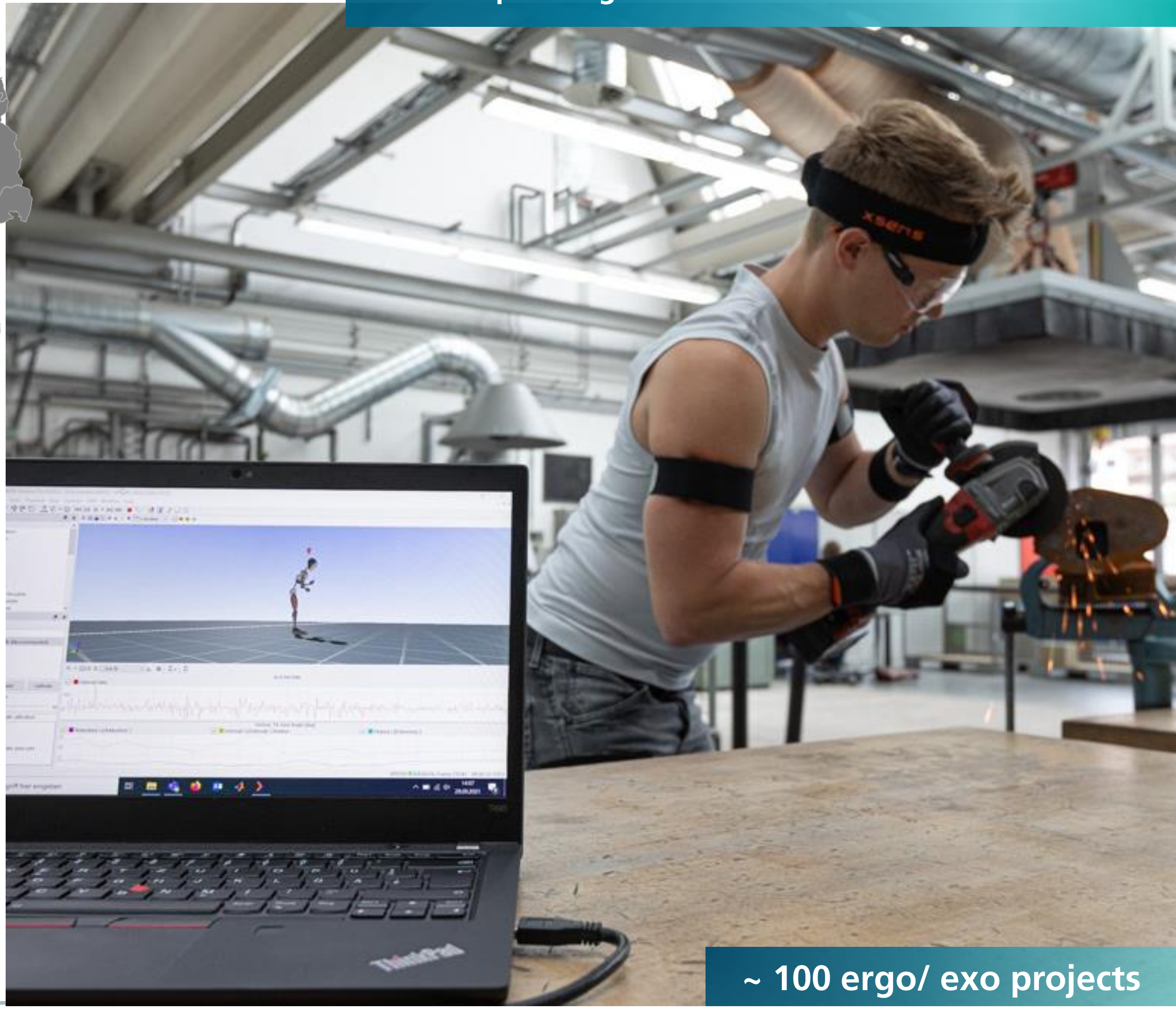
- Motion capture
- company requirements and framework conditions

Ergonomic analysis

- Examination of movement data according to critical movement sequences and combinations based on biomechanical, orthopedic, sports-, training- and work- science principles
- Crosschecking with etiologies of frequently occurring MSDs

Relief concepts

1. Technical Measures
2. Organizational Measures
3. Personal Measures



~ 100 ergo/ exo projects

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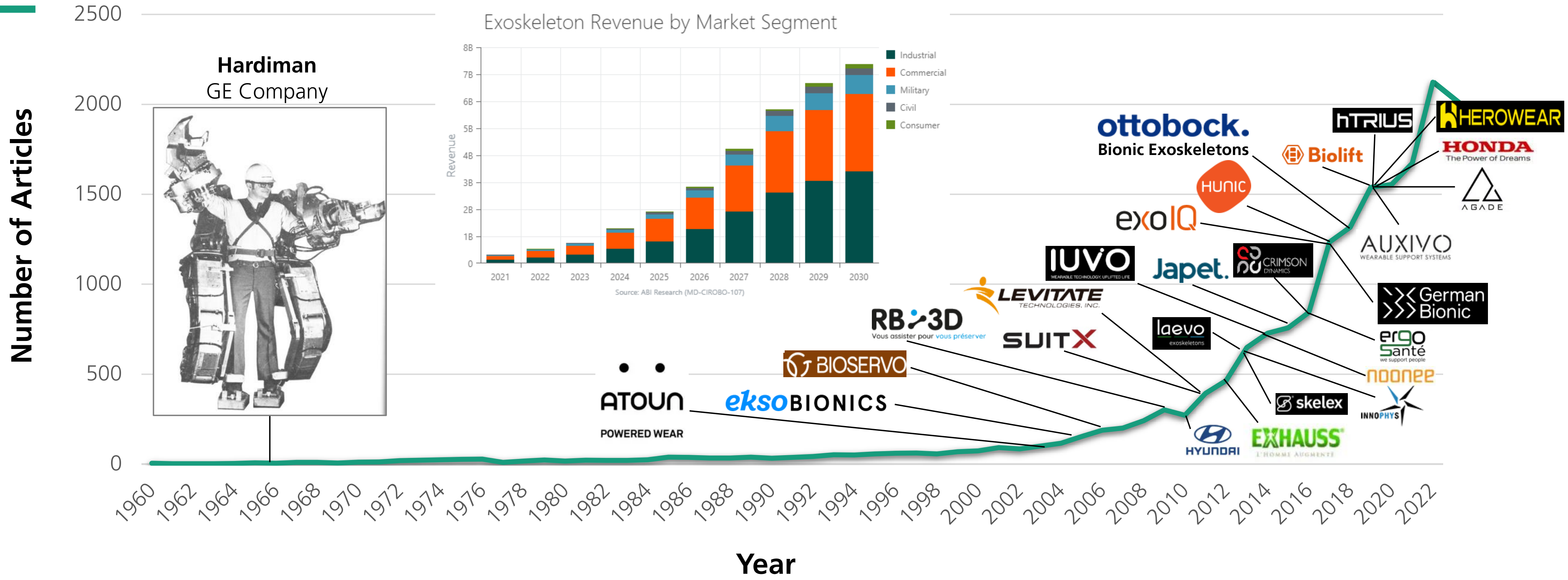
Exoskeletons

Historical development of societal interest



Number of found articles in the research database Scopus under the search term exoskeleton* between 1960 and 2023 (© www.scopus.com, as of September 10, 2024) with start dates of relevant companies or company divisions of occupational exoskeletons.

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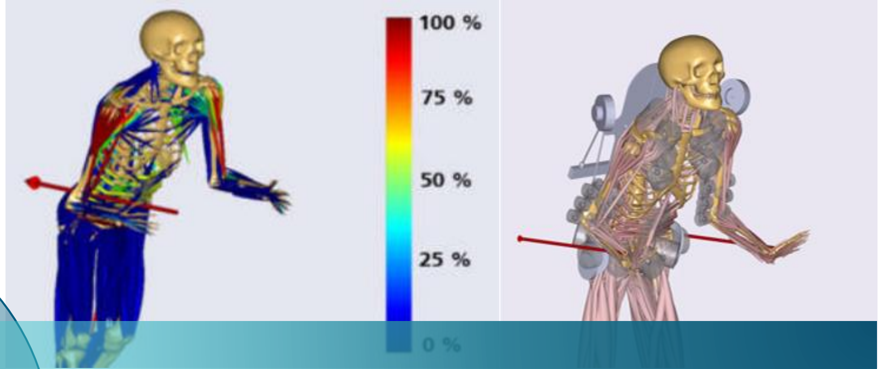
Research areas in the field of exoskeletons

Approach to develop and evaluate occupational exoskeletons

Ergonomic and biomechanical requirement analysis (in the field and in the laboratory)



Conceptualisation and evaluation with digital human-exoskeleton models

Evaluations in the field and the laboratory with human-in-the-loop experiments

Design and development of passive, semi-active and active exoskeletons

How we keep an overview

DIN

NA 023–00-08
GA „Exoskelette“

AWMF

AWMF clinical guidelines

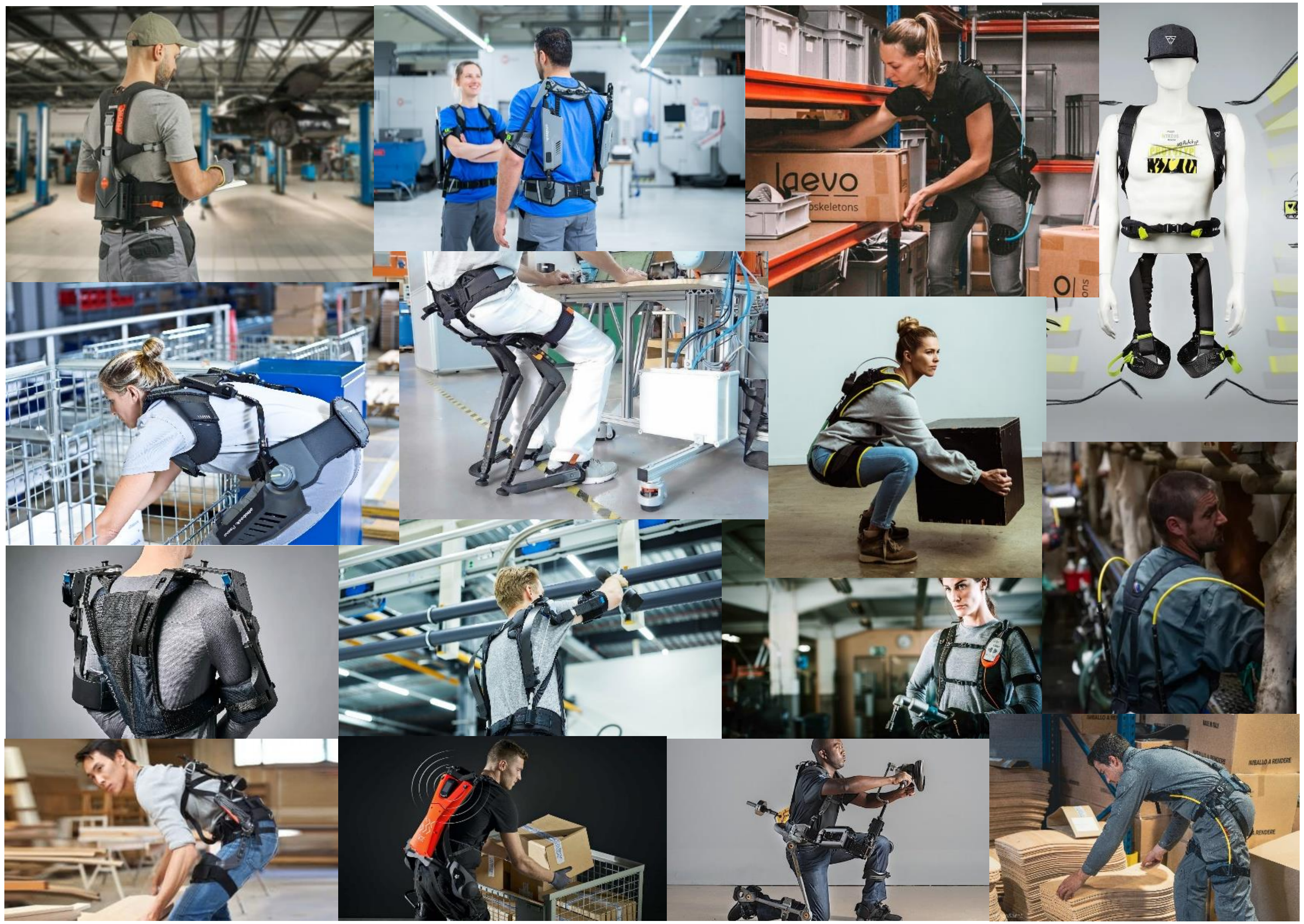
Use of exoskeletons in an occupational context for primary, secondary and tertiary prevention of work-associated musculoskeletal disorders

EXOWORKATHLON

ASTM Committee F48 Exoskeletons and Exosuits

Soon: ASTM international F.48 Standard

Study design for standardized evaluation of exoskeletons



Standard Assessment Format

Prospective study approach to assess occupational exoskeletons

EXOWORKATHLON

M.Sc.
Verena Kopp

M.Sc.
Mirjam Holl

Dr. med.
Urs Schneider



Motivation

- Industrial exoskeletons are fascinating devices.
- They are developed and used in order to facilitate some work functions and to prevent from musculoskeletal diseases. They may even improve the work output quality in some cases.

EXOWORKATHLON

- Creates short work scenarios with "exoskeleton potential" with applying industry and OSHA
- Compares intra-individually 1h work with exoskeleton vs 1h work without exoskeleton
- The used exoskeletons are named, but there is no data output per exoskeleton device, but only comparative data of work with vs without exoskeleton.
- Exoworkathlon is an ASTM work item to get standard test format in assessing occupational exoskeletons.

ASTM INTERNATIONAL

Exoworkathlon

Overview of existing Parcours

EXOWORKATHLON

Exoworkathlon

Key facts

- So far a total of **125 test persons**
- distributed on **six different Parcours** with **different exoskeletons**

Results:

✓ Significant reduction of subjective stress

✓ Significant reduction of muscle activity in corresponding muscles

✓ Significant reduction of metabolic stress during welding

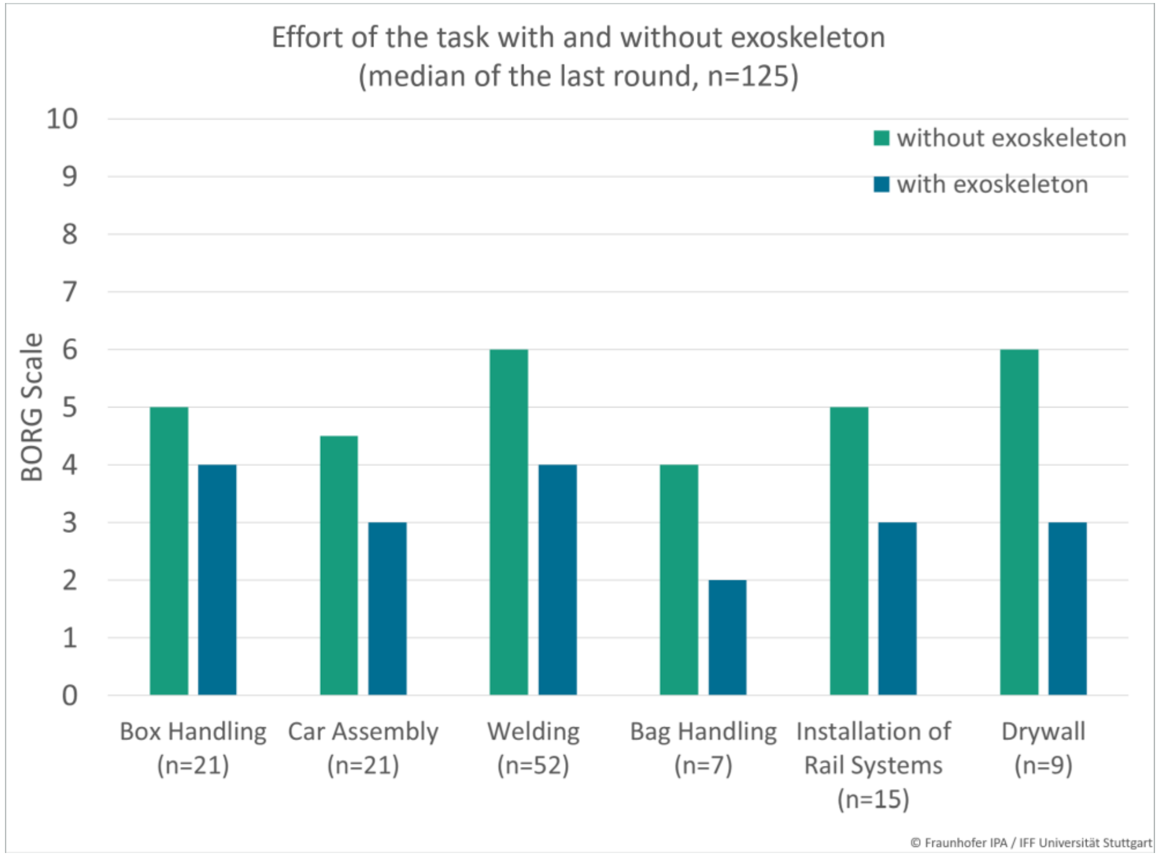
✓ Significant improvement in welding quality

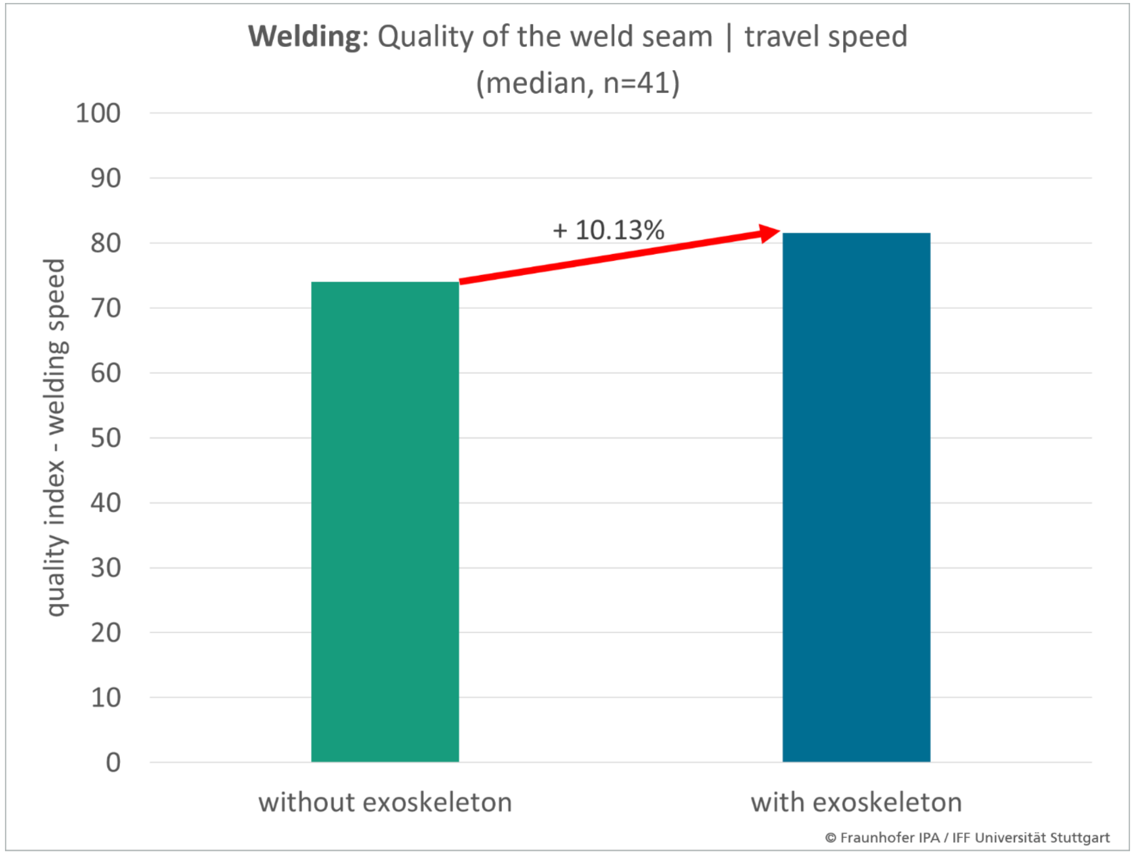
Contributing Experts: Dr. Hensel-Unger (AUDI), Israel Benavides (FORD), Mrs Richter (WELDPLUS), Mrs Pohlmann (SLV NORD), Dr. Ulrich Glitsch (DGUV IFA), Dr.-Ing. Sascha Wischnieswski (BAUA)

Contributing Partners: Audi AG, Ford-Werke GmbH, Fa. Kliewe, Lufthansa Technik AG, Fa. Mayr-Wilhelm, Fa. PS-Apparatebau, Fa. Rudolf Richers, Hilti, Wilhelm-Maybach Schule Stuttgart, Steinbeisschule Stuttgart

Exoworkathlon

Extract of results





Further info and results: https://www.exoworkathlon.de

Digital Ergonomics

Application of digital human models

Anthropometrics:
- Percentile
- Age
- Somatotype
- …

Structure:
- Skeleton
- Volume skeleton
- Musculoskeletal system
- …

Manipulation:
- Posture
- Motion
- Forces
- …

Environment:
- Tools
- Humans
- Work station
- **Exoskeleton**
- …

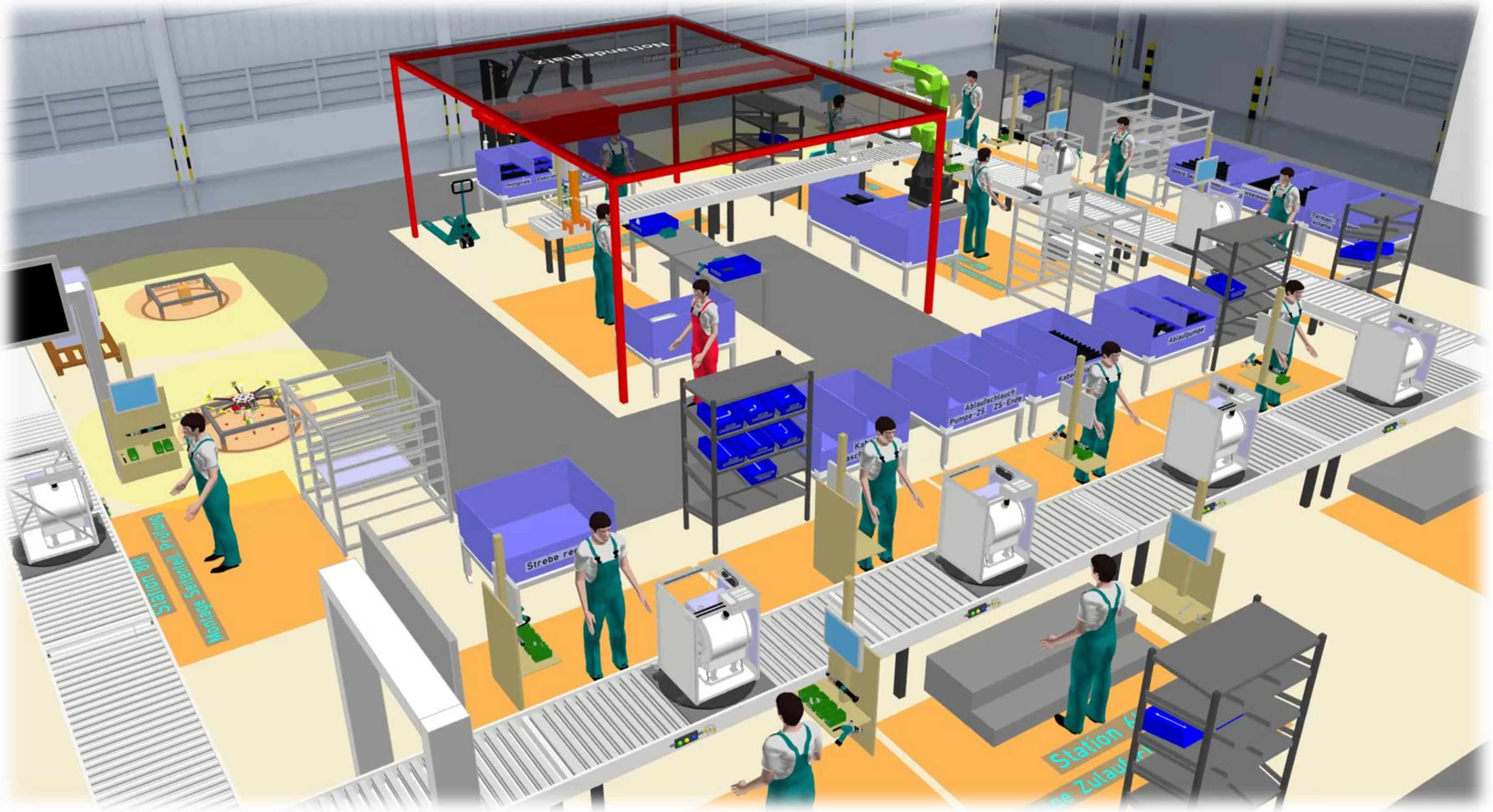
Digital Human Modeling

Analyses:
- Motion analysis
- Fatigue analysis
- Posture analysis
- Load analysis
- Stress analysis
- …

Adapted extract of DIN EN ISO 6385:2004-05 (DIN EN ISO 6385, 2004)

Holistic Ergonomic Work Design

Digital work planning tools



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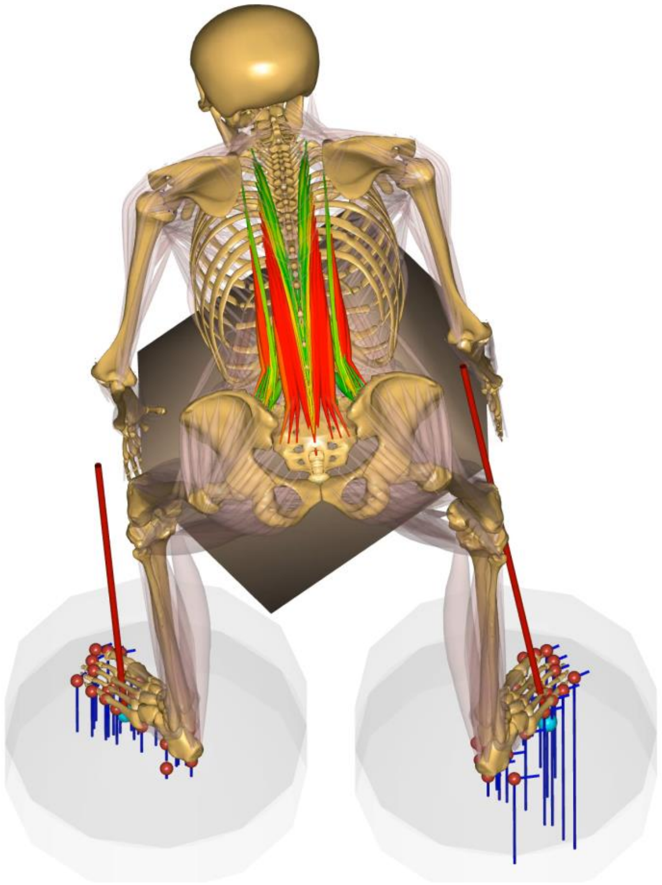
“Technology is the answer, but what was the question?”

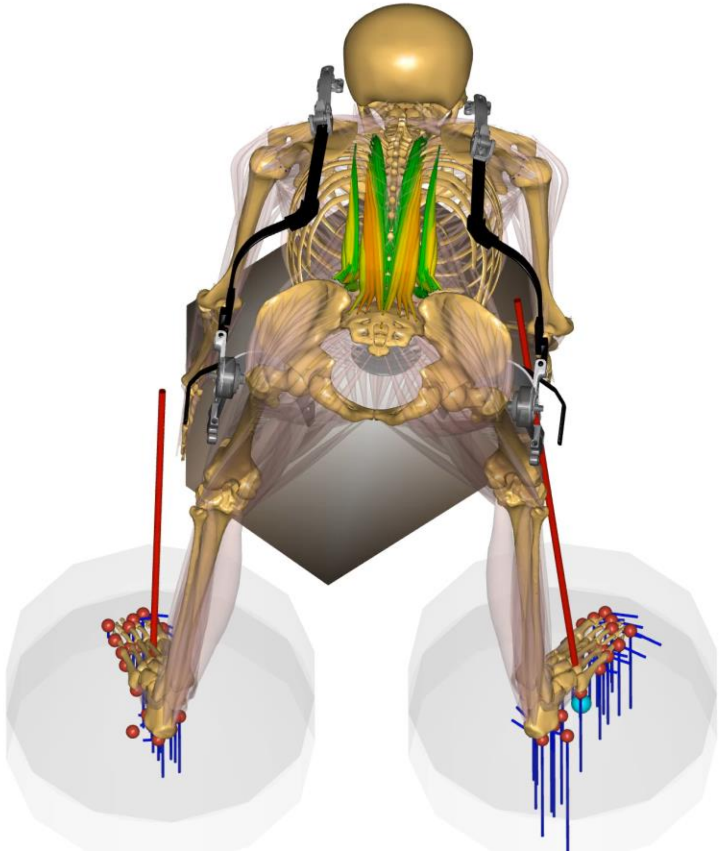
Cedric Price, 1966

Architect

Biomechanical Evaluation

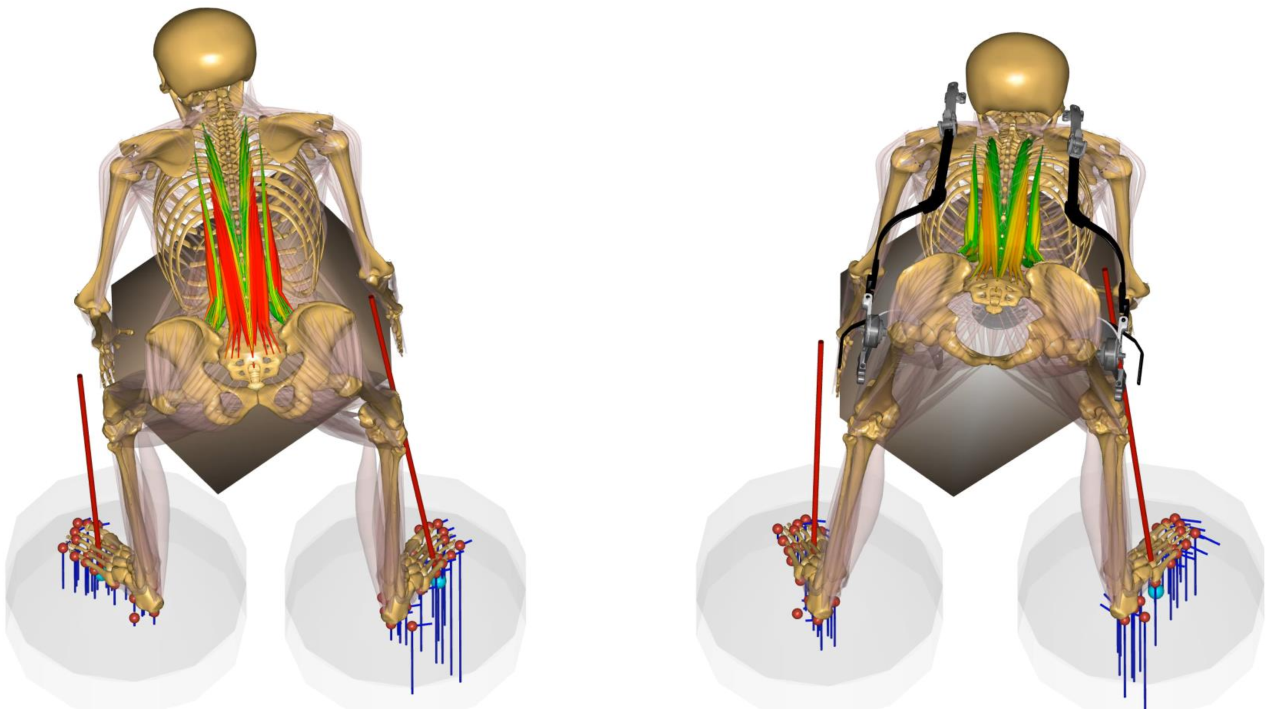
Musculoskeletal modeling

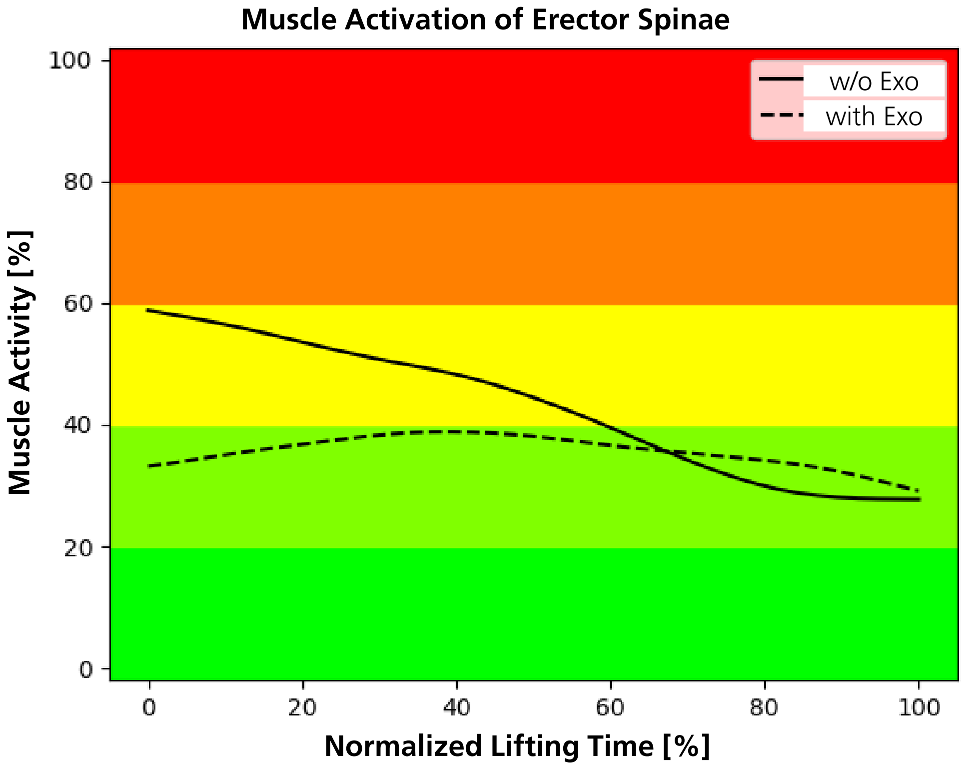




Classification of Dynamic Muscle Stress

Lifting a box





Classification of dynamic muscle activation [1,2]	**< 30,00 %**	**< 60,00 %**	**< 80,00 %**	**> 80,00 %**

[1] - Schlick, Christopher; Bruder, Ralph; Luczak, Holger (2018): Arbeitswissenschaft. 4. Aufl. Berlin, Heidelberg: Springer.

[2] - Koether, R., B. Kurz und U. A. Seidel (2001). Betriebsstättenplanung und Ergonomie: Planung von Arbeitssystemen. 1. Aufl. München, Wien: Carl Hanser Fach-buchverlag.

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Funded by

Federal Ministry of Education and Research

Research Project DigitalExonomics

Digital Work Design and Ergonomics Assessment for the Use of Occupational Exoskeletons

Project partners

imk industrial competence

the captury

Fraunhofer IPA

OTH Ostbayerische Technische Hochschule Regensburg

Associated partners

DAIMLER TRUCK

Universitätsklinikum Tübingen
Institut für Arbeitsmedizin, Sozialmedizin und Versorgungsforschung
unrestricted grant by SÜDWESTMETALL

Mercedes-Benz

DB

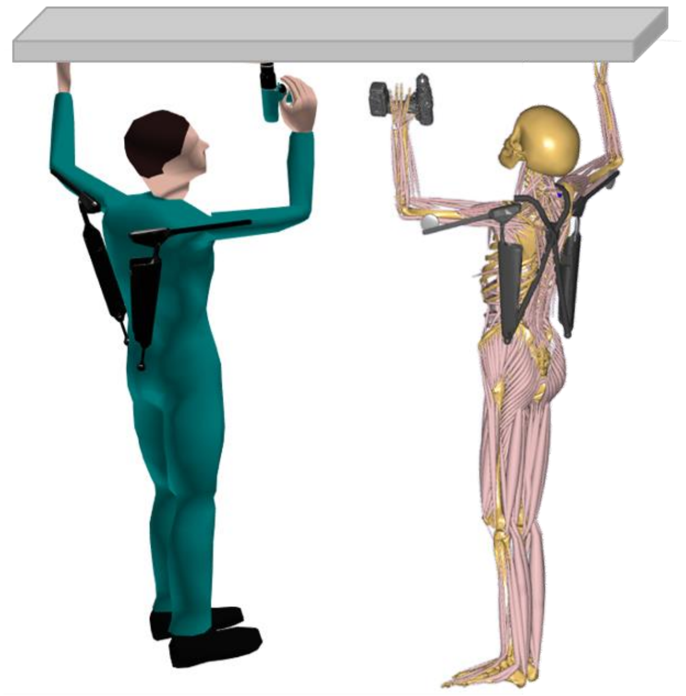
AnyBody Technology

ottobock.

HUNIC

ASKLEPIOS Klinikum Bad Abbach

DIGITAL EXONOMICS

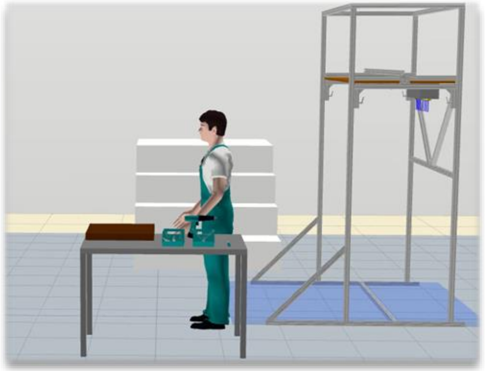


Lab Study
Modeling methods

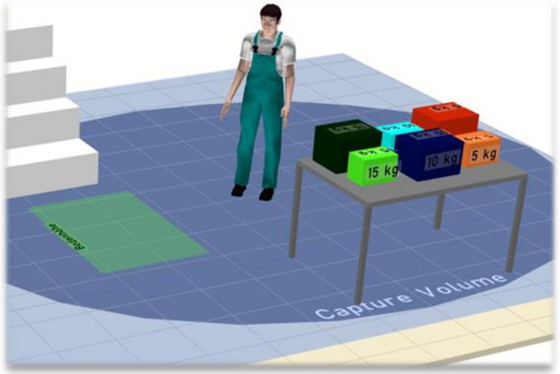
- Measurement of 17 test persons (5 external from Schenker AG and DB-FZI)
- Digitally planned work setup and procedure in ema Work Designer

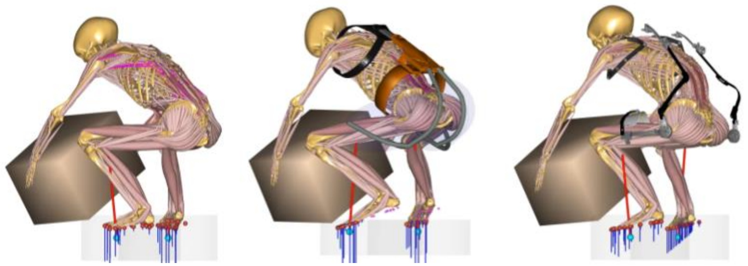
Test person during the laboratory study and marker model from motion capture (Qualisys)

Use case shoulder:



Use case back:

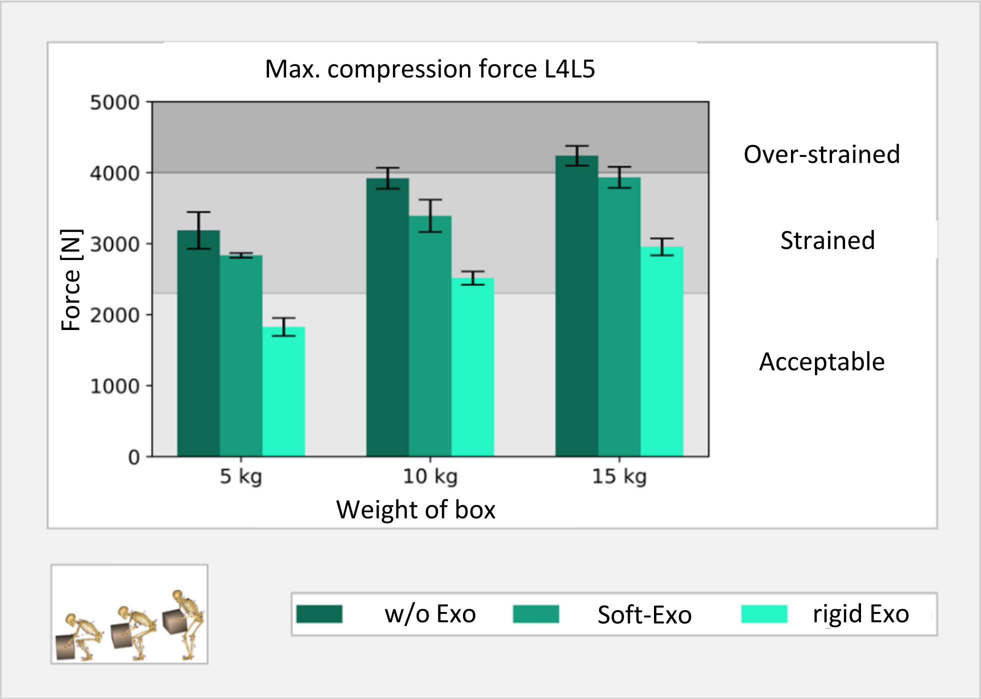




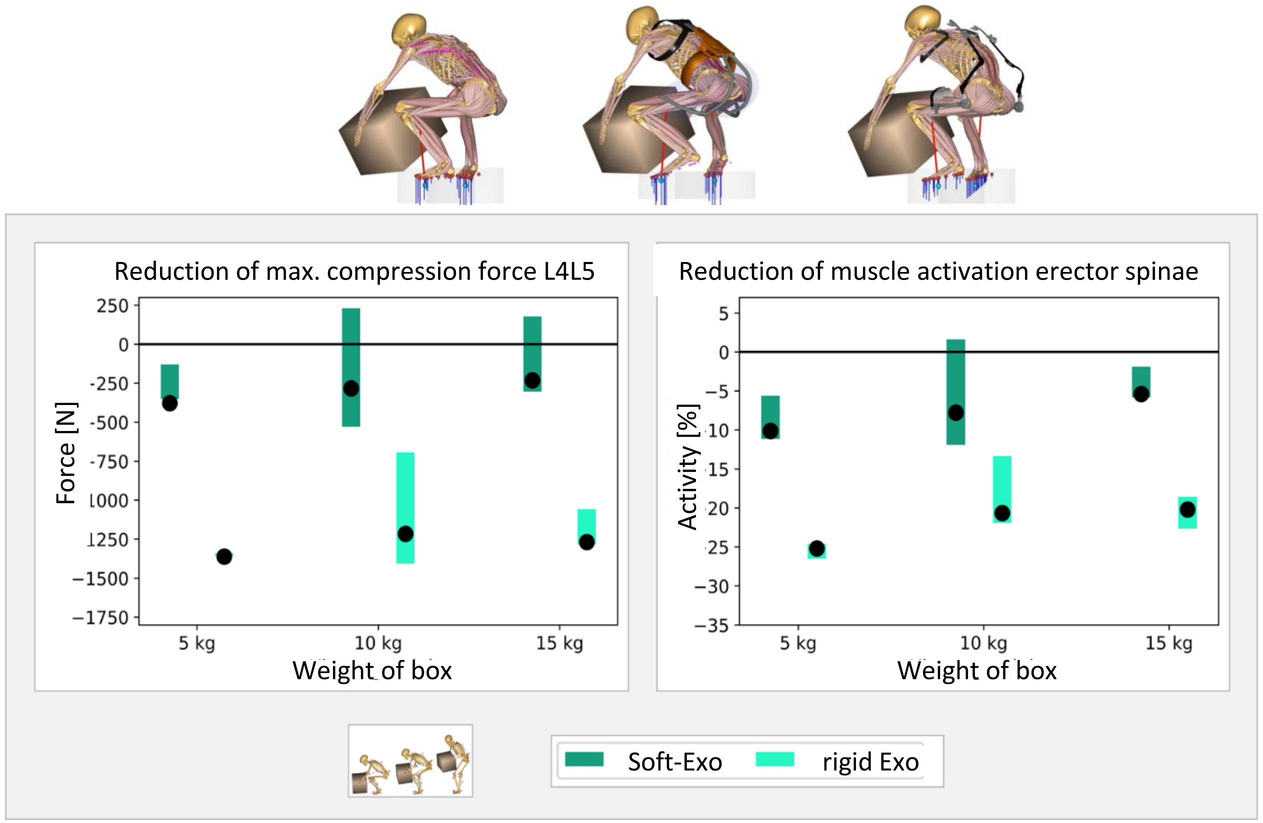
Multi-body simulation in AnyBody

Intended Biomechanical Effects

Results of one test subject



Back strain limits based on Dortmund guideline gender and age specific values (Jäger 2018)



Difference over the movement sequences with mean value over the 4 movement sequences

< 0: Reduction due to the exoskeleton
> 0: Increase due to the exoskeleton.

Jäger, Matthias (2019): Die „Revidierten Dortmunder Richtwerte". In: Zbl Arbeitsmed 69 (5), S. 271–289. DOI: 10.1007/s40664-019-0356-3.

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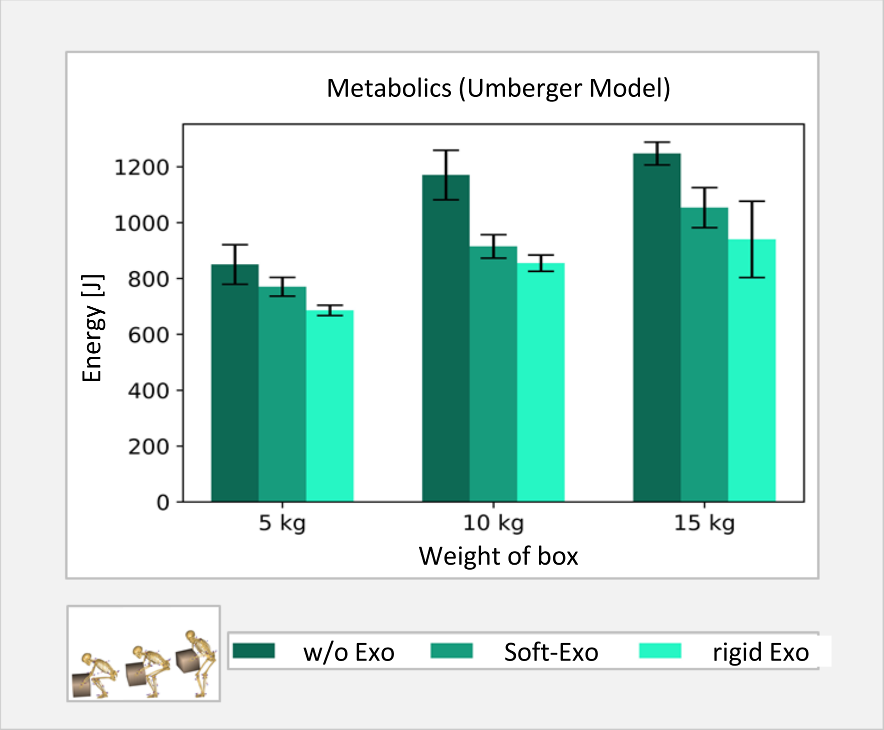
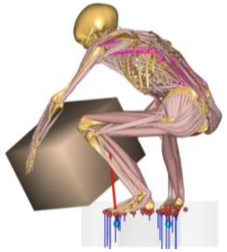
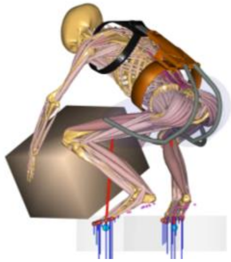
Not Intended Biomechanical Effects

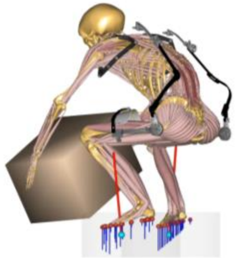
Results of one test subject



Comparative values from studies by Bergmann et al.







Holistic Evaluation of Muscle Activities

Biomechanical Body Map for back exoskeletons

Shoulder-Arm Muscles

→ Envelope of Activities of ALL Upper Extremity Muscles

Trunk Muscle Groups

→ Back Muscles (M. Multidi, M. Erector Spinae, M. Quadratus Lumborum, M. Semispinales, M. Spinalis) (meaned Activity)

→ Abdomen Muscles (M. Transversus, M. Rectus Abdominis, M. Obliquus Externus, M. Obliquus Internus) (meaned Activity)

Main Mobilizers

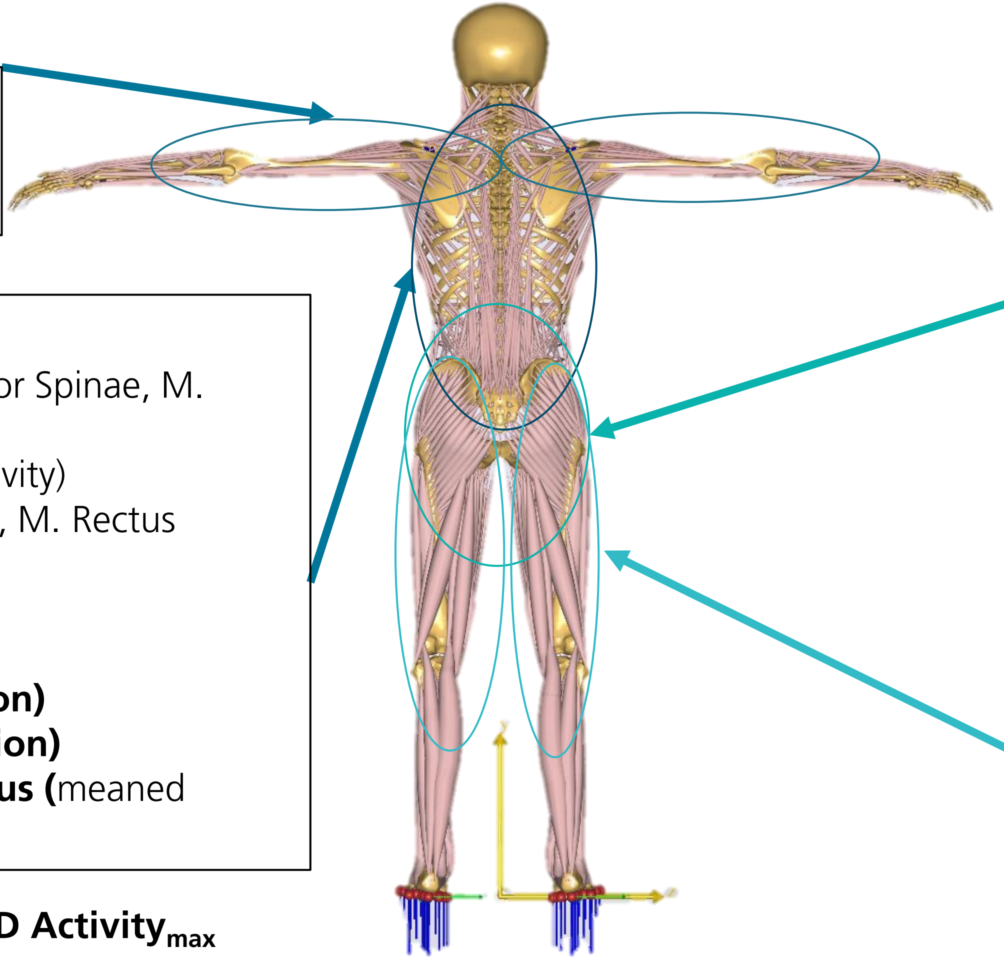
→ M. Erector Spinae (Trunk Extension)

→ M. Rectus Abdominis (Trunk Flexion)

→ M. Obliquus Internus und Externus (meaned Activity) **(Trunk Rotation)**

In dynamic motions: Activity$_{mean}$ AND Activity$_{max}$

In static motions: Activity$_{mean}$



Hip Muscles

→ Flexor Muscles (M. psoas major, M. iliacus, M. rectus femoris, M. sartorius)
(Right meaned Activity & Left meaned Activity)

→ Extensor Muscles (M. gluteus maximus, M. semitendinosus, M. semimenbranosus, M. biceps femoris)
(Right meaned Activity & Left meaned Activity)

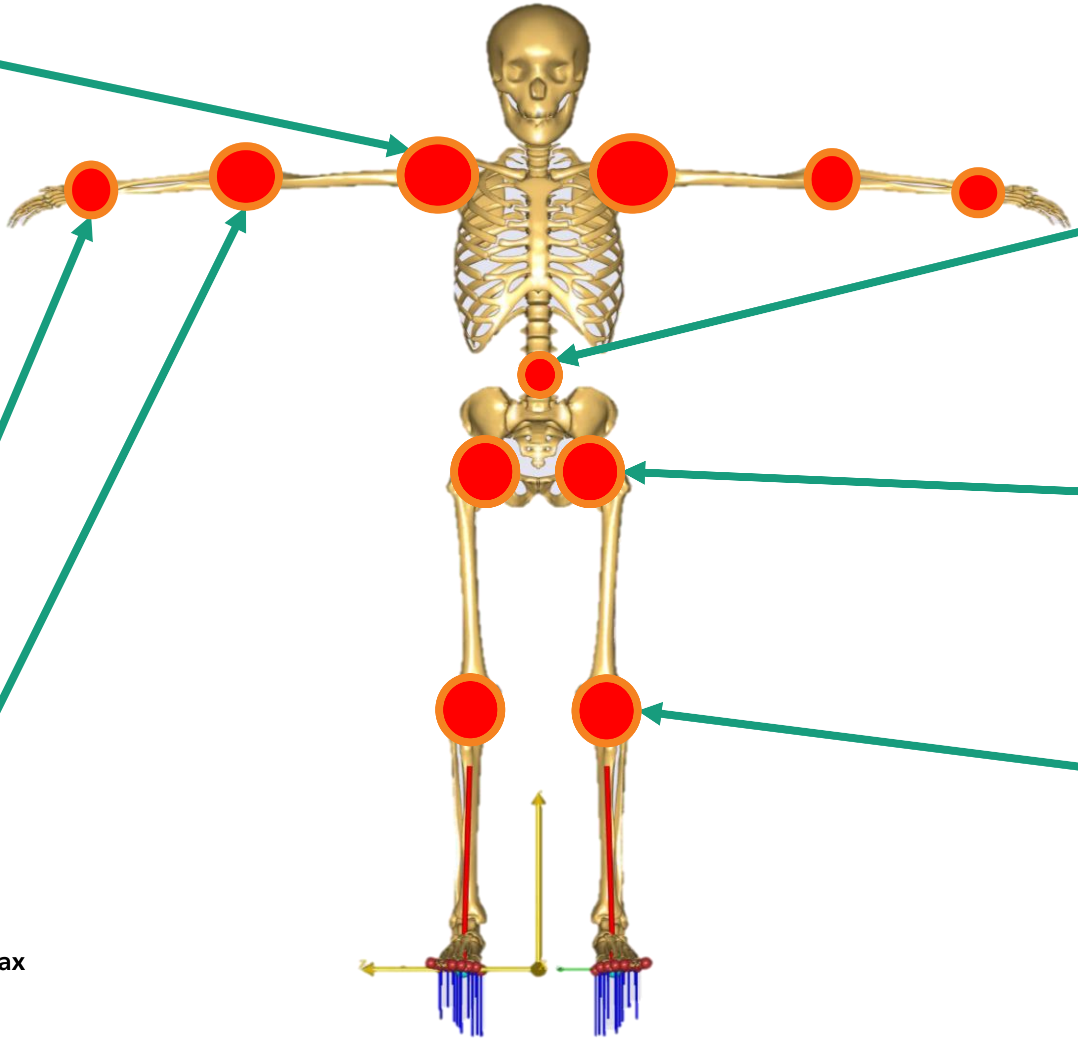
Knee Muscles

→ Extensor Muscles (M. vastus intermedius, M. vastus medialis, M. vastus lateralis, M. rectus femoris)
(Right meaned Activity & Left meaned Activity)

→ Flexor Muscles (M. gracilis, M. sartorius, M. gastrocnemius, M. semitendinosus, M. semimenbranosus, M. biceps femoris, M. plantaris, M. Popliteus)
(Right meaned Activity & Left meaned Activity)

Holistic Evaluation of Joint Kinetics

Biomechanical Body Map for back exoskeletons



Glenohumeral Joint
→ **Compression Force**
→ **Stability Indicator**
(Left&Right)

Wrist Joint
→ **Resultant Force**
(Left & Right)

Elbow Joint
→ **Resultant Force**
(Left & Right)

Lumbar Joint L4L5
→ **Compression Force**
→ **Shear Force**

Hip Joint
→ **Resultant Force**
(Left & Right)

Knee Joint
→ **Resultant Force**
→ **AnteroPosterior Force**
(Left & Right)

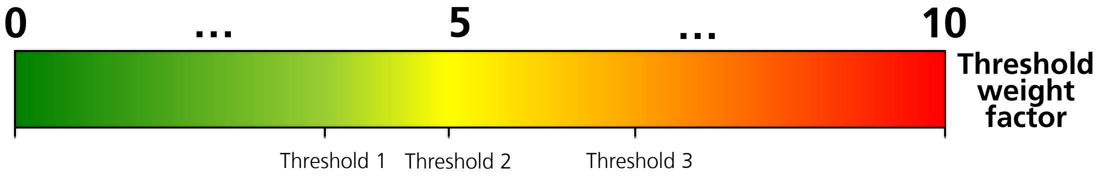
In dynamic motions: F_{mean} **AND** F_{max}
In static motions: F_{mean}

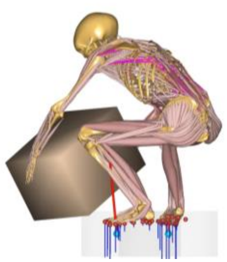
Biomechanical Body Heat Map

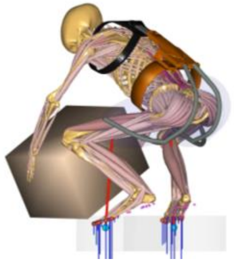
Joint Kinetics – results of one test subject - lifting a box (36 trials)

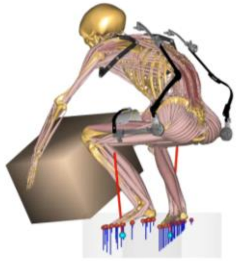
Parameter	no Exo 5 kg	Soft Exo 5 kg	Rigid Exo 5 kg	no Exo 10 kg	Soft Exo 10 kg	Rigid Exo 10 kg	no Exo 15 kg	Soft Exo 15 kg	Rigid Exo 15 kg	Thresholds
GHJ compression force left [N]	484.09 ± 243.77	353.72 ± 138.73	406.12 ± 159.12	712.5 ± 245.58	597.53 ± 247.09	634.41 ± 252.82	812.29 ± 273.44	681.5 ± 234.69	895.36 ± 296.62	[300, 500, 800]
GHJ compression force right [N]	561.0 ± 334.72	357.57 ± 185.08	364.06 ± 149.25	824.13 ± 436.81	617.56 ± 342.77	634.69 ± 360.55	997.59 ± 450.58	713.8 ± 303.72	823.61 ± 295.22	[300, 500, 800]
GHJ stability indicator left	4.3 ± 3.2	3.27 ± 3.27	2.05 ± 0.68	4.18 ± 1.4	4.02 ± 2.56	2.51 ± 0.98	3.28 ± 0.84	2.55 ± 0.54	1.97 ± 0.28	[0.5, 1, 1.5]
GHJ stability indicator right	5.07 ± 4.71	4.51 ± 2.6	3.02 ± 1.19	8.18 ± 7.16	5.78 ± 3.48	3.42 ± 1.11	12.9 ± 28.91	4.88 ± 3.48	3.06 ± 4.92	[0.5, 1, 1.5]
EJ resultant force left [N]	327.5 ± 167.57	256.63 ± 103.46	273.65 ± 70.33	458.01 ± 133.06	376.2 ± 96.09	361.87 ± 129.98	619.78 ± 115.05	578.84 ± 118.01	524.26 ± 97.22	[450, 700, 1000]
EJ resultant force right [N]	235.02 ± 109.73	206.75 ± 79.45	230.43 ± 54.29	363.59 ± 58.38	307.9 ± 56.72	320.22 ± 55.94	451.77 ± 96.82	446.23 ± 76.67	503.67 ± 99.31	[450, 700, 1000]
WJ resultant force left [N]	211.94 ± 156.67	160.75 ± 94.53	191.23 ± 90.84	294.49 ± 212.27	225.4 ± 135.41	218.54 ± 220.65	415.62 ± 165.6	307.25 ± 100.51	237.02 ± 140.12	[200, 400, 600]
WJ resultant force right [N]	225.74 ± 179.04	170.59 ± 94.39	130.73 ± 68.48	155.82 ± 137.87	141.55 ± 104.05	121.71 ± 94.04	231.71 ± 117.33	204.38 ± 99.38	108.83 ± 47.15	[200, 400, 600]
HJ resultant force left [× BW]	2.46 ± 0.8	3.11 ± 0.56	2.02 ± 0.69	3.04 ± 1.09	3.16 ± 1.14	2.98 ± 1.24	3.15 ± 1.63	3.99 ± 1.6	2.95 ± 1.21	[3.0, 4.0, 5.0]
HJ resultant force right [× BW]	2.56 ± 1.03	2.35 ± 1.08	2.41 ± 1.04	2.91 ± 0.87	3.19 ± 0.95	2.67 ± 0.88	4.04 ± 0.84	3.96 ± 1.12	3.5 ± 0.95	[3.0, 4.0, 5.0]
KJ resultant force left [× BW]	2.65 ± 1.03	2.66 ± 0.78	3.1 ± 1.32	2.77 ± 1.25	2.41 ± 1.02	3.22 ± 1.34	2.68 ± 1.57	2.68 ± 0.99	3.42 ± 1.78	[0.0, 4.0, 5.0]
KJ resultant force right [× BW]	3.16 ± 1.48	2.47 ± 1.48	3.83 ± 1.67	3.1 ± 1.4	2.75 ± 1.11	3.68 ± 1.7	3.63 ± 1.16	2.84 ± 0.99	4.69 ± 1.67	[0.0, 4.0, 5.0]
KJ anteroposterior force left [N]	1812.63 ± 885.7	1699.05 ± 733.91	2014.93 ± 945.48	1851.86 ± 1155.48	1521.49 ± 966.92	2087.85 ± 1111.5	1721.25 ± 1311.92	1427.9 ± 962.27	2259.28 ± 1294.91	[1300, 2200, 2600]
KJ anteroposterior force right [N]	2235.71 ± 1148.62	1749.55 ± 1130.51	2478.13 ± 1113.61	2187.28 ± 1169.17	1876.43 ± 979.85	2495.07 ± 1209.4	2332.4 ± 1151.12	1685.72 ± 1029.45	3004.83 ± 1048.53	[1300, 2200, 2600]
LJ L4L5 compression force [N]	3076.48 ± 1021.86	2439.86 ± 585.19	1840.22 ± 445.23	3608.99 ± 1019.81	2797.49 ± 670.68	2383.58 ± 648.61	4223.2 ± 1199.84	3221.54 ± 737.42	2810.26 ± 753.87	[2000, 3500, 4000]
LJ L4L5 shear force [N]	695.3 ± 249.75	427.76 ± 110.74	376.8 ± 111.61	808.34 ± 241.69	496.78 ± 126.92	499.65 ± 157.18	948.57 ± 281.4	586.67 ± 135.47	610.46 ± 179.8	[500, 700, 1000]

Notes:
- GHJ = Glenohumeral Joint
- EJ = Elbow Joint
- WJ = Wrist Joint
- HJ = Hip Joint
- KJ = Knee Joint
- LJ = Lumbar Joint



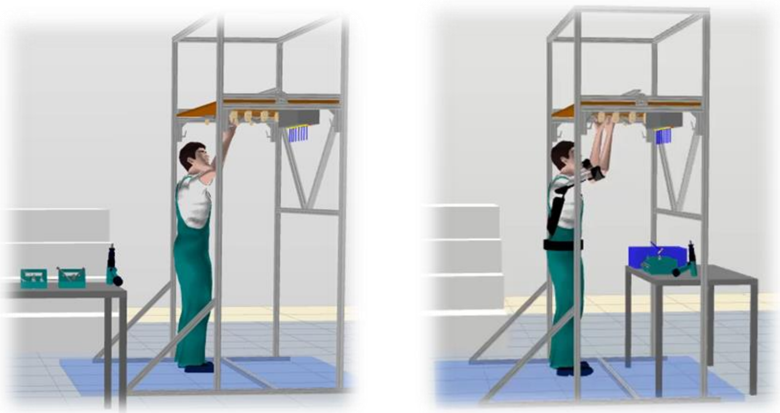


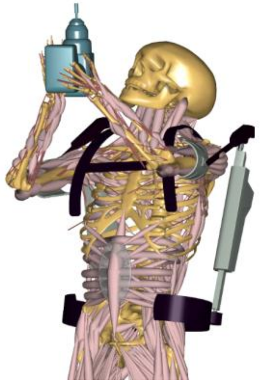




Digital Ergonomic (Exoskeleton) Evaluation

Ergonomic assessment approaches needed so far





Digital Ergonomics (Exoskeleton) Score based on the Biomechanical Heat Map to evaluate Ergonomic Measures (Exoskeletons)

Exoskeleton Analysis	w/o Exoskeleton	Ottobock Shoulder
Total Body [pts]	61	47.5
Posture [pts]	61	46.5
Forces [pts]	0	0
Manual Load Handling [pts]	0	0
Extra Points [pts]	0	1
Upper Extremities [pts]	**87.36**	**87.36**
∑ Force & Frequency & Gripping [pts]	7.2	7.2
∑ Hand / Arm / Shoulder Postures [pts]	4	4
∑ Additional Factors [pts]	0	0
∑ Duration of repetitive Tasks [pts]	7.8	7.8

Simplified integration in EAWS??!!

ESO-EAWS [1]

Exo-LiFFT: Ergo Assessment

Repetitions
1000 lifts

Lever Arm
40 cm 16 in

Object Weight
15.0 kg 33.0 lb

Peak Load Moment
59 Nm

Exo Moment
30 Nm

Cumulative Damage Without Exo
0.014
LBD Risk Without Exo
45.5

Cumulative Damage With Exo
0.005
LBD Risk With Exo
33.4
Exo Reduces LBD Risk By
26.6 %

Simplified consideration of effects??!

Exo-LiFFt [2]

[1] - Fondazione Ergo-MTM Italia (2022): Exoskeleton certification. Homepage. Online accessed under: https://www.eaws.it/exoskeleton-certification/, 13/09/2024.

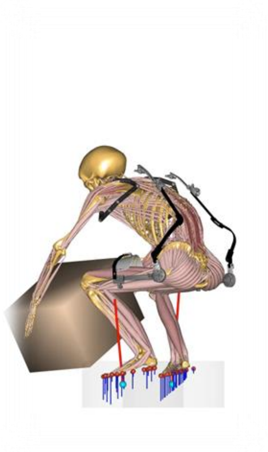
[2] - Zelik, Karl E.; Nurse, Cameron A.; Schall, Mark C.; Sesek, Richard F.; Marino, Matthew C.; Gallagher, Sean (2022): An ergonomic assessment tool for evaluating the effect of back exoskeletons on injury risk. In: Applied ergonomics 99, S. 103619. DOI: 10.1016/j.apergo.2021.103619.

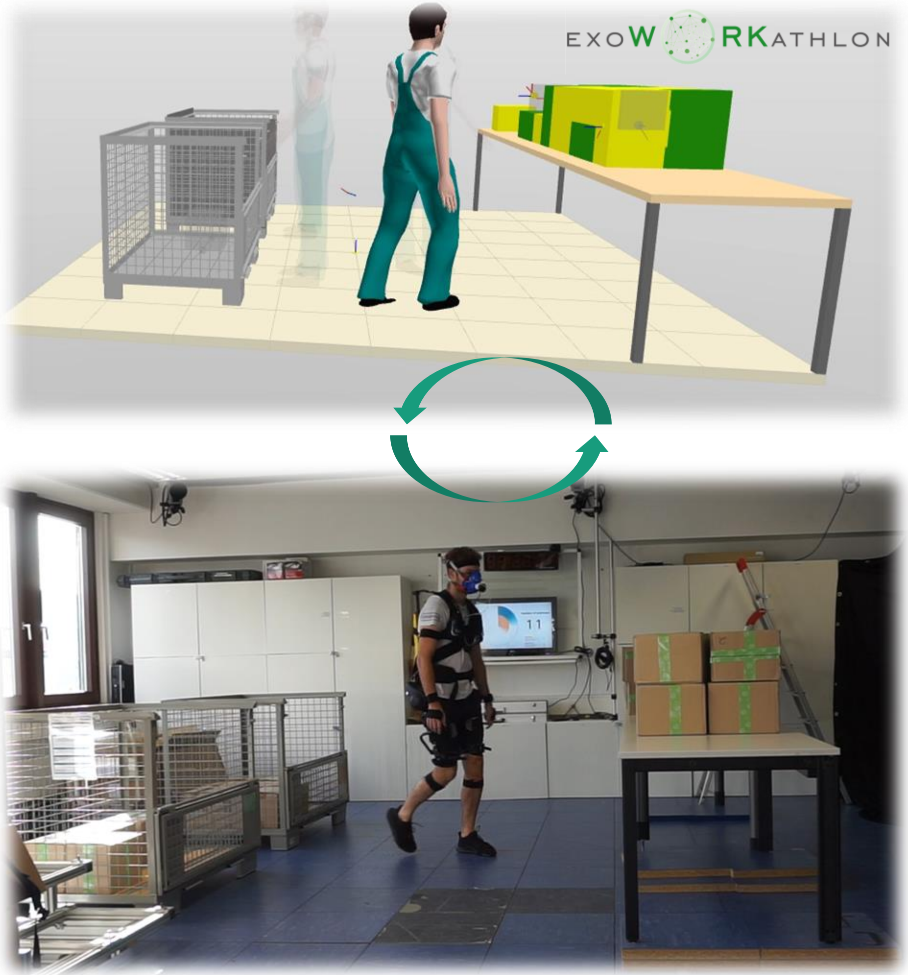
Future Work - Digital Ergonomic (Exoskeleton) Evaluation

To support ergonomic adoption of occupational exoskeletons

- Validation and Verification Procedure for musculoskeletal models
- Development of an evaluation method for occupational exoskeletons in digital work planning tools
- Demonstration on Exoworkathlon Parcours

→ We are aiming for a consensus on a practicable and scientifically credible assessment method for occupational exoskeletons!





Wrap Up

Digital ergonomic tools

- The better the physical stress on the musculoskeletal system is understood, the better ergonomic measures can be derived.
- Digital tools like musculoskeletal modeling can help to better understand physical stress.
- To improve user-friendliness, sophisticated biomechanical investigations can increasingly be integrated into planning software tools.

- Digital tools can be used to evaluate ergonomic measures in advance before they are implemented in real work environment.

- The topic field is complex. We work in various committees in order to be in dialogue with as many stakeholders as possible – and we are looking forward to networking with you on your challenges.

DIN NA 023–00-08 GA „Exoskeletons“

ASTM INTERNATIONAL
Committee F48 on Exoskeletons and Exosuits

EAWS 2.0 CONSORTIUM

WearRAcon EUROPE

AWMF
Arbeitsgemeinschaft der Wissenschaftlichen Medizinischen Fachgesellschaften e.V.

MTM

Thank you for your attention!
Feel free to reach out to us!

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