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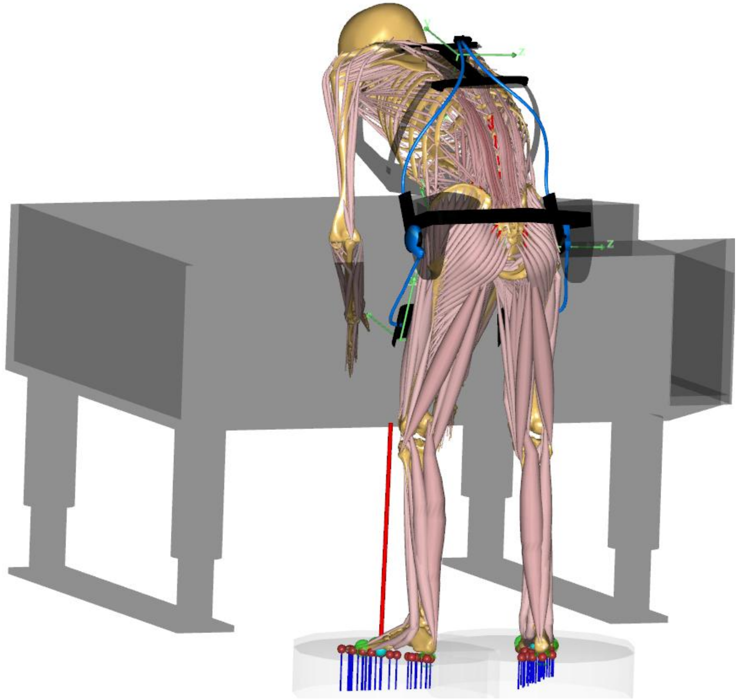
Biomechanical Simulation of Passive Back-Support Exoskeletons: Effects of Actuator Strength on Load and Contact Stress



Presented by:

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Jay Kim, *PhD*

November 5th, 2025

Who are we?

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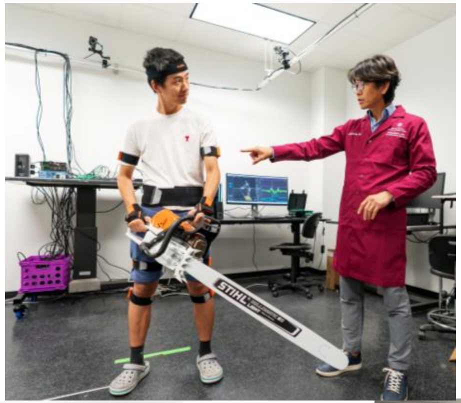
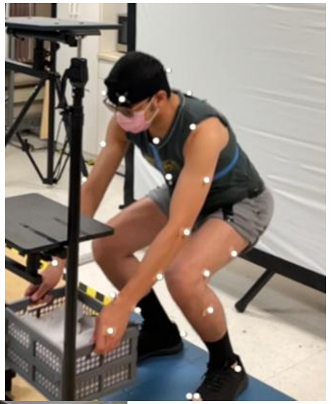
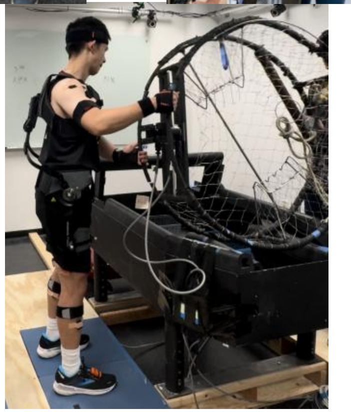
Occupational Ergonomics and Biomechanics (OEB) Lab

School of Public Health




Motivation

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The global pandemic of **low back pain!**

Most prevalent work-related musculoskeletal disorder (WMSD) [1]

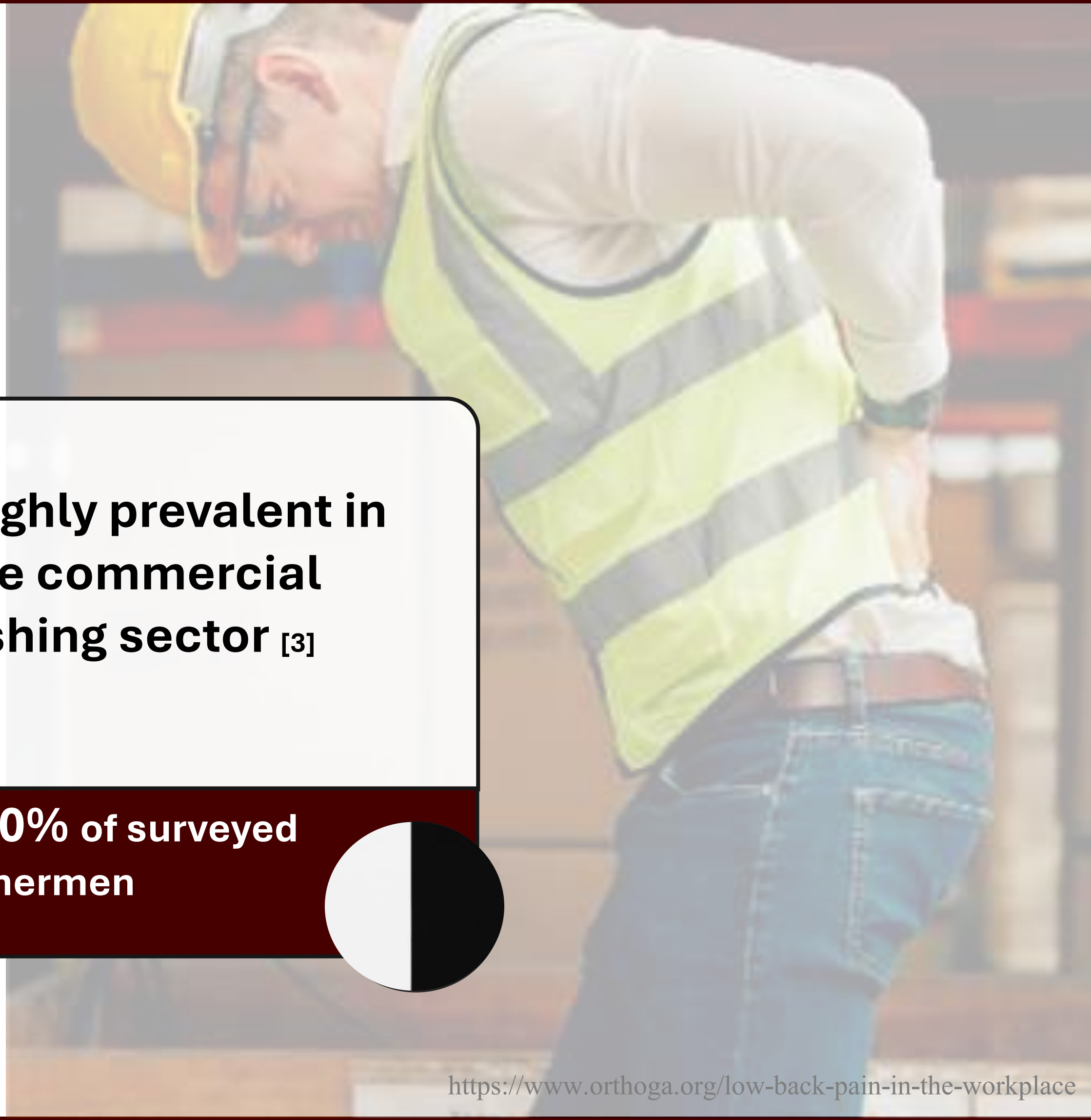
~40% of all WMSD incidence cases

15% of the workers in the US lost 10 workdays on average in 2022 [2]

= 260 million workdays lost

Highly prevalent in the commercial fishing sector [3]

~50% of surveyed fishermen



https://www.orthoga.org/low-back-pain-in-the-workplace

[1] BLS, 2023, [2] Ferreira et al. 2023, [3] Fulmer et al., 2017

Introduction

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Occupational back-support exoskeletons (BSE):

Viable ergonomic intervention to reduce low back biomechanical load and work-related injuries

❖ **Biomechanical benefits:**
Reduced muscle activity, spinal loads, metabolic effort, and perceived exertion and discomfort in the back. [4,5,6,7]

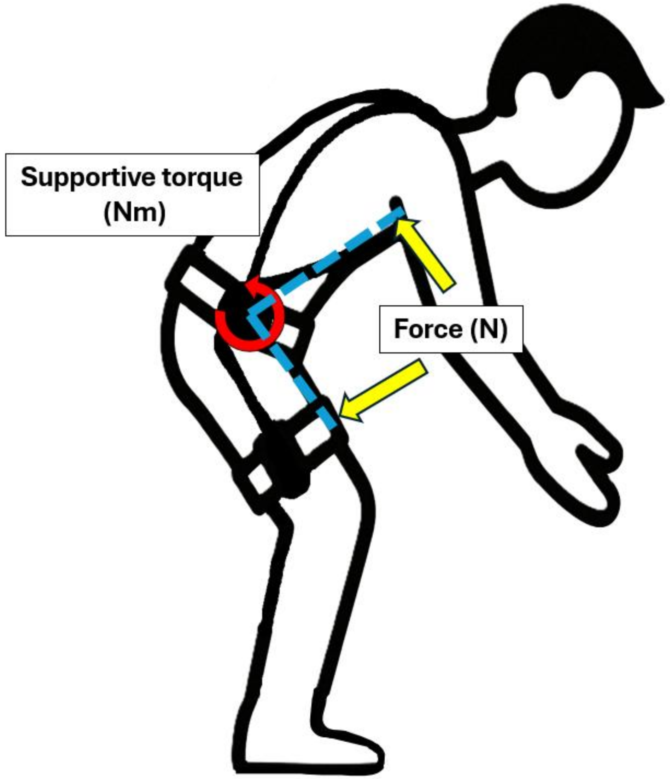
❖ **Potential side effects:**
Restricted mobility, increased activity of trunk flexor and leg muscles, localized discomfort. [8,9,10,11]

https://exoskeletonreport.com

[1] Luger et al., 2023, [2] Madinei et al., 2020, [3] Baltrusch et al., 2020, [4] Kozinc, Baltrusch, et al., 2021, [5] Schwartz et al., 2023, [7] Alemi et al., 2019, [8] Kranenborg et al., 2023

Exoskeleton supportive torque:

The amount of torque/force transferred from the exoskeleton to the user at each posture (bending angle)



- ✓ Directly affect potential benefits and side effects [1]
- ✓ Must be matched with the task and user requirements

[1] Natali et al., 2020

Occupational Exoskeletons:
from laboratory tests to field implementation

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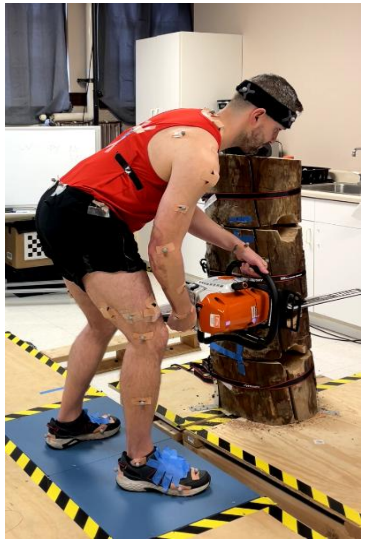
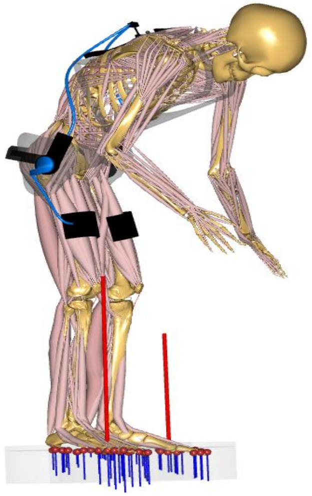
Evaluating the baseline demands of a given task (no assistance) → **Possible unloading effect of various exoskeletons and torque levels** → **Human-in-loop experiments with selected exos/torque levels** → **Field studies with realistic conditions** → **Field implementation and long-term impacts**

Field studies with realistic conditions → **Specific field-related challenges** → **Human-in-loop experiments with selected exos/torque levels**



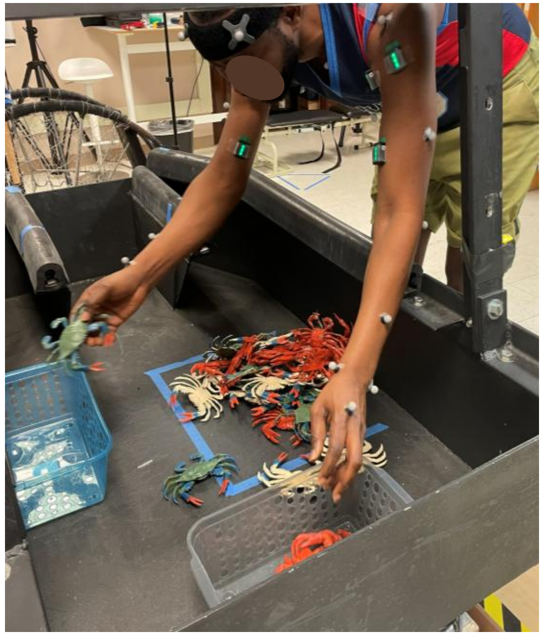
What muscles or joints are highly loaded?

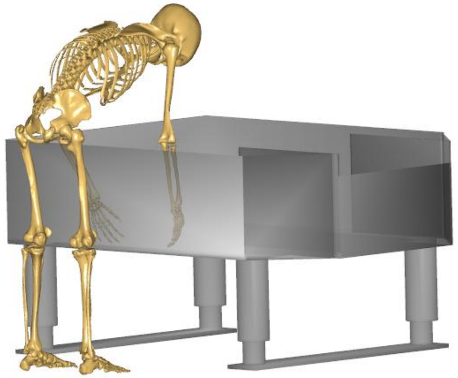


What exo and torque level can match population and task demands??

Gathering subjective feedback and validating simulation results (e.g., muscle activation)

Laboratory experiment





- **Targeted task: crab sorting**

Sorting 40 mock-up crabs by color on a sorting table used in the West Coast Dungeness crab fishing fleet

- **20 healthy male adults**

- **Full-body kinematics** using an optical motion capture system

Combined human-exoskeleton modeling:
Kinematic analysis

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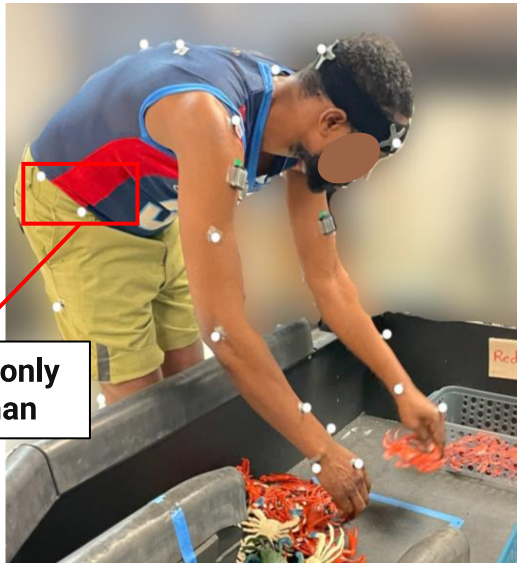
Only human movement data were collected

Human-Exo kinematic constraints

Equal to additional DoFs (Determinate)
Higher than additional DoFs (Over-determinate)

(hard/soft constraints)

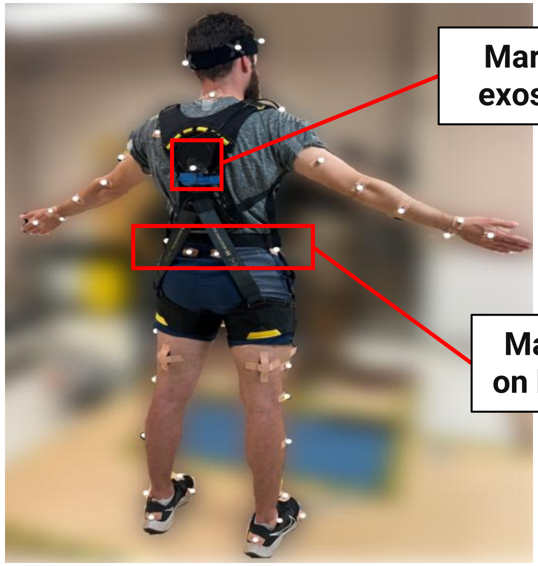


Human and exoskeleton movement data were collected independently

Mocap driven

(Over-determinate)

(soft constraints)



Human and exoskeleton movement data were collected partially

MoCap driven +
Human-Exo kinematic constraints

(Over-determinate)

(hard/soft constraints)

Combined human-exoskeleton modeling:
Kinetic analysis

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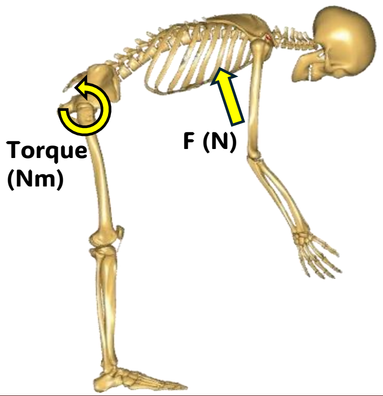
Is a virtual model of the exoskeleton available?

No

Adding exoskeleton torque/force directly to the human model: no interface

Mohamed Refai et al., 2024

- Torque is assumed to operate in an idealized way
- Doesn't incorporate the mass and inertia of the device

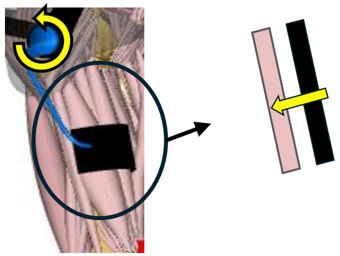


Yes

Reaction forces and moments - can be/not be associated with kinematic constraints

Tröster et al., 2024

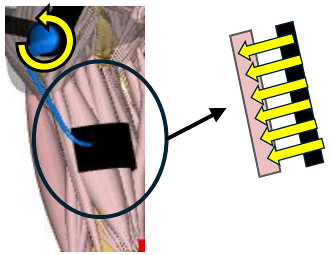
- Modeling the interaction as point forces
- Limited by additional exoskeleton DoFs



Rigid-body contact model - defining contact elements between two rigid bodies

Chander et al., 2022

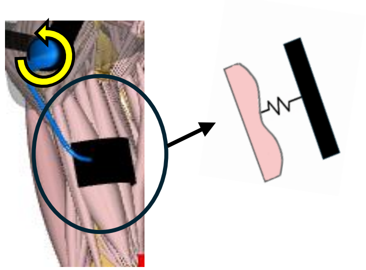
- Requires detailed geometry and careful tuning of contact parameters
- Complexity: possible interaction between muscle force and interface force



Viscoelastic contact model - incorporating the behavior of the soft biological tissue

Sánchez-Villamañán et al., 2019

- Highly complex involving numerous parameters



Methods: Human-Exoskeleton interface modeling

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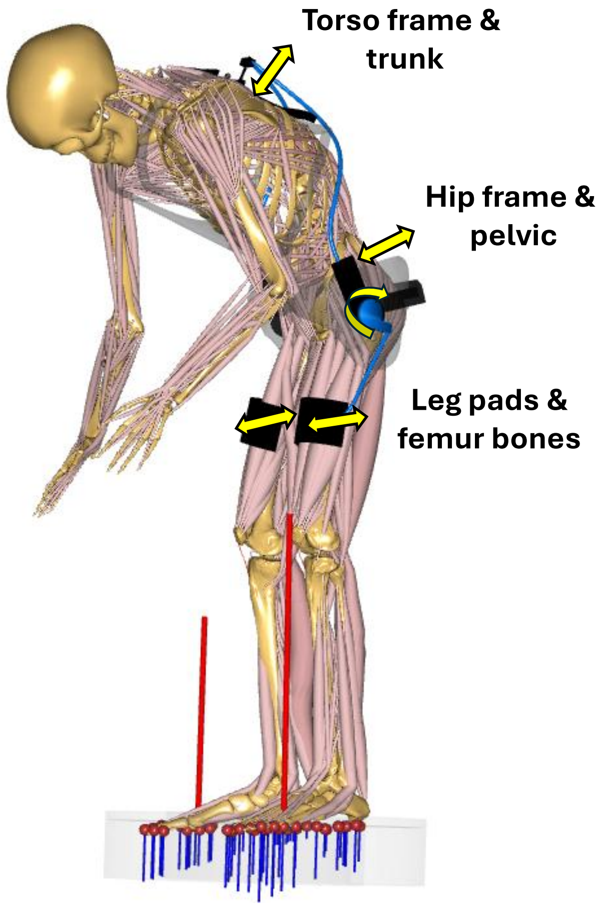
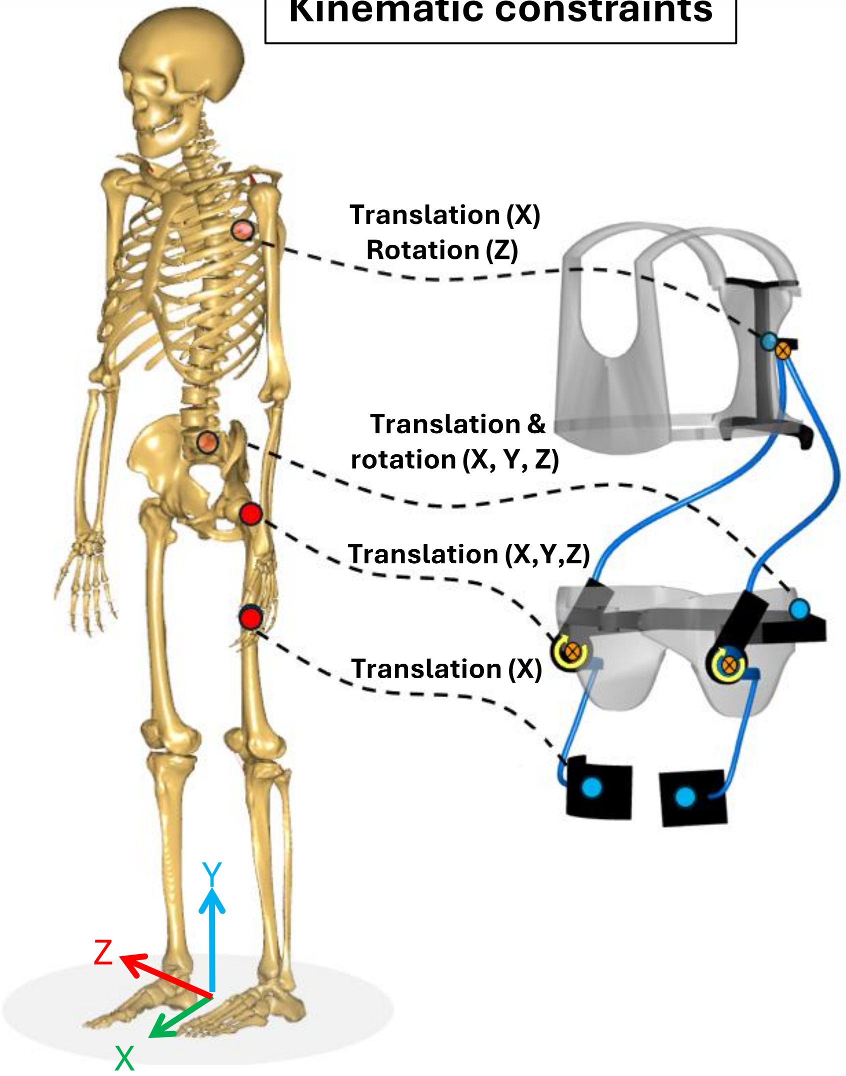
Interaction forces



Kinematic constraints



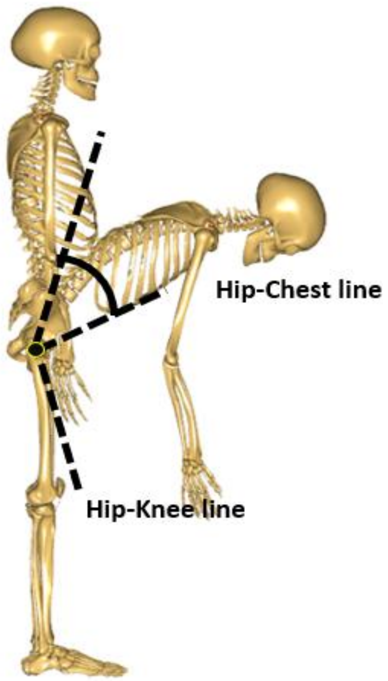
Exoskeleton structure

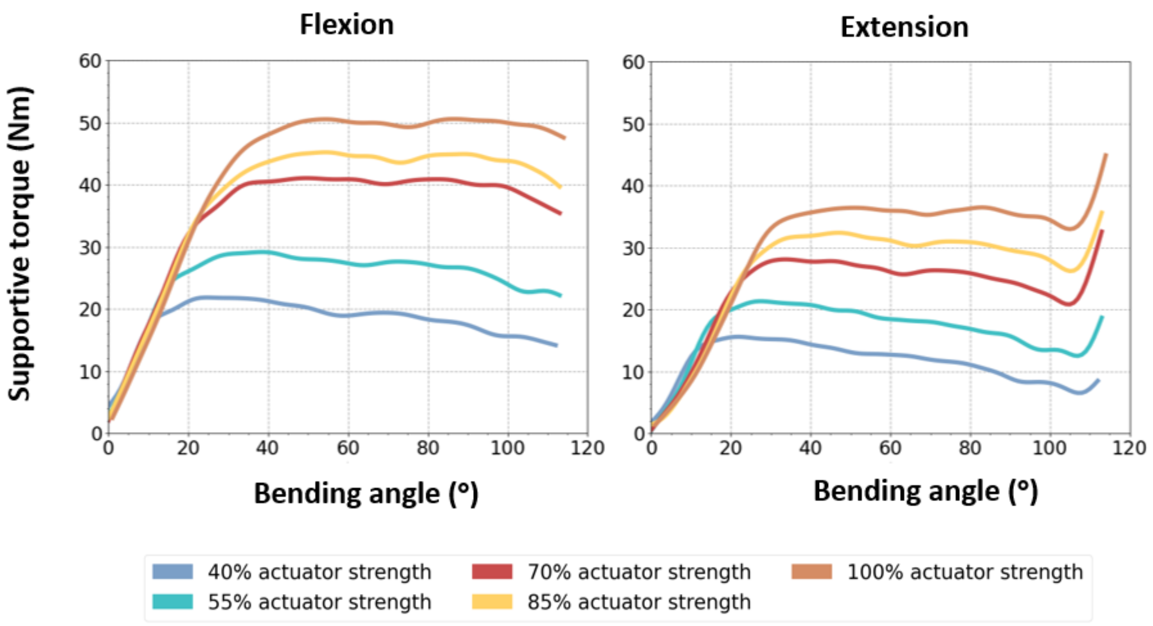
6 * 6 Segments = 36 DoFs ↑
1 Weld joint + 3 Revolute joints =
21 constraints ↓

Kinematics
⇒ 15 additional DoFs ↓
(At least 15 kinematic connections/constraints between the human and exoskeleton models)

Kinetics
Exactly 15 reaction forces/moments

Methods: Calculating assistive torque of the exoskeleton





[1]

Bending angle

Direction of angular velocity

→ MATLAB →

BSE assistive torque for each participant through the task

Two-dimensional interpolation function

[1] Harmelen et al., 2022

Outcome measures

1. Muscle activity

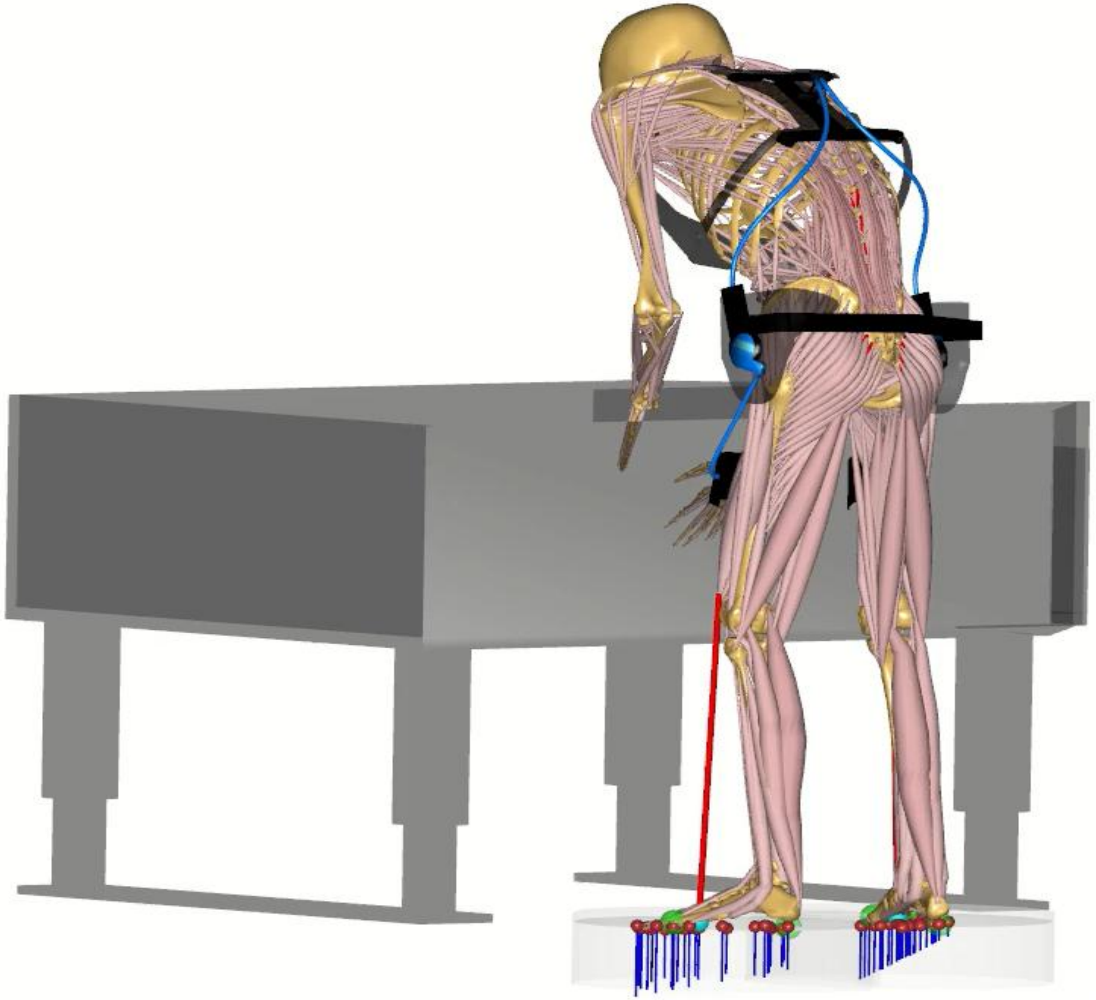
- **Trunk extensor** (erector spinae muscle group: longissimus, iliocostalis, and spinalis)
- **Trunk flexor** (rectus abdominis, internal and external obliques) muscles

2. Spinal compression and AP shear forces

- Lumbosacral (L5/S1) joint

3. Human-BSE interaction forces

- Chest
- Thigh

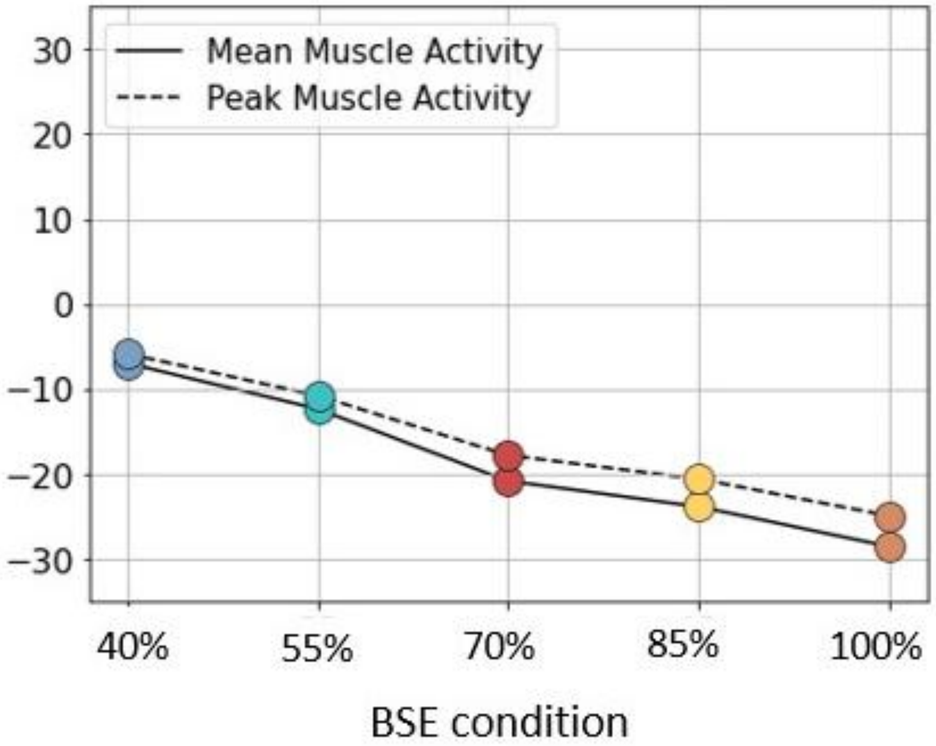


Results: Muscle Activity

Percentage change in muscle activity with each support level of the BSE compared to the baseline

Trunk extensors

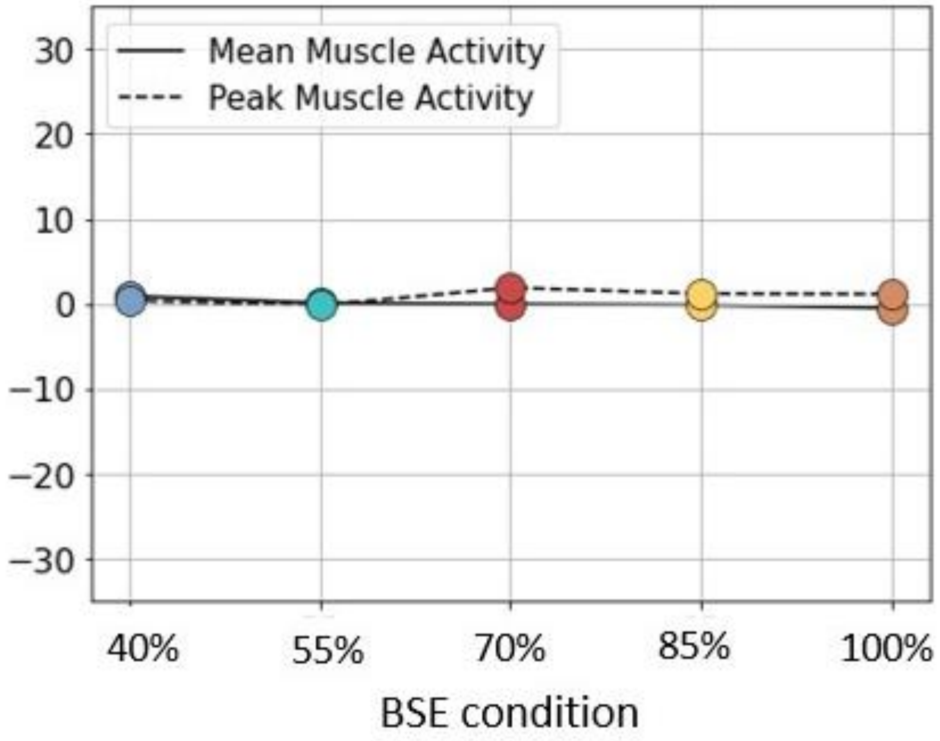
Baseline: **30.8%**



❖ Significant reduction with all support levels, ranging from 6% to 29%

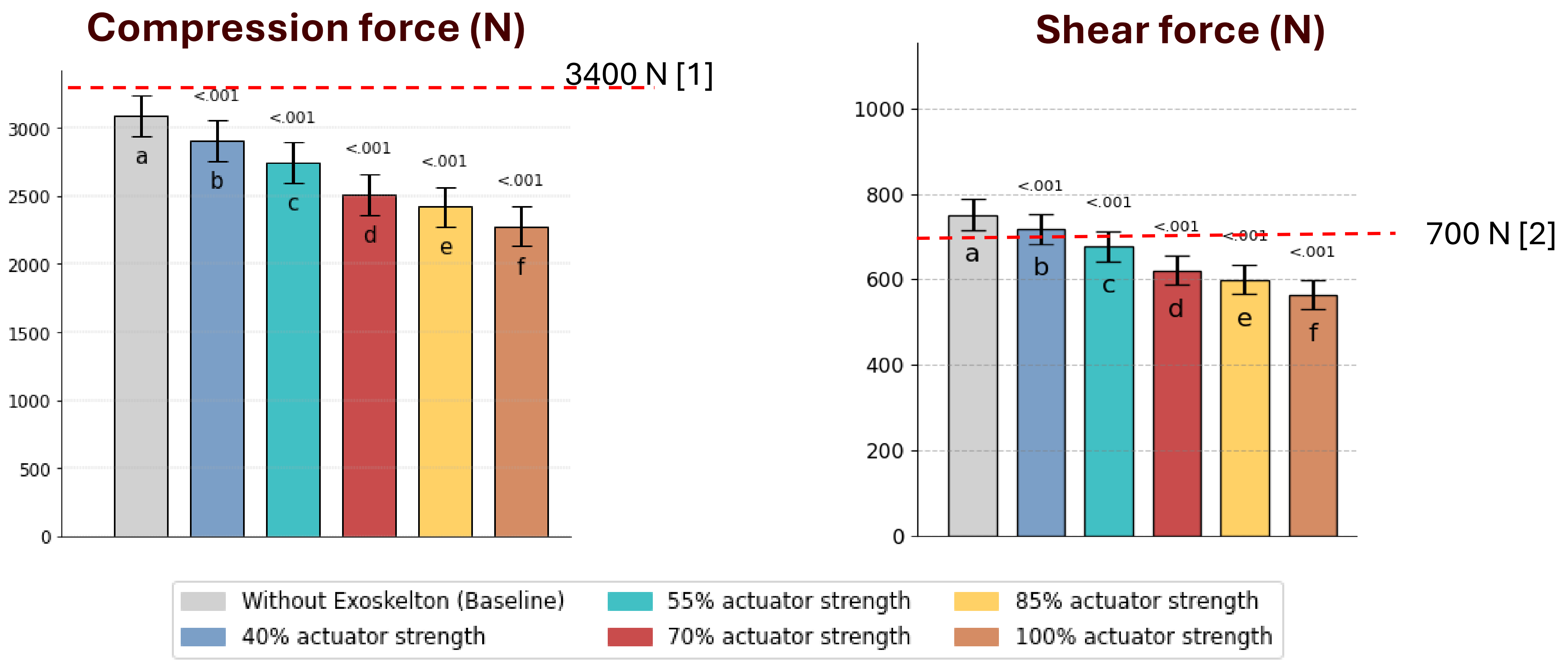
Trunk flexors

Baseline: **3.09%**



❖ No effect (< 2% change)

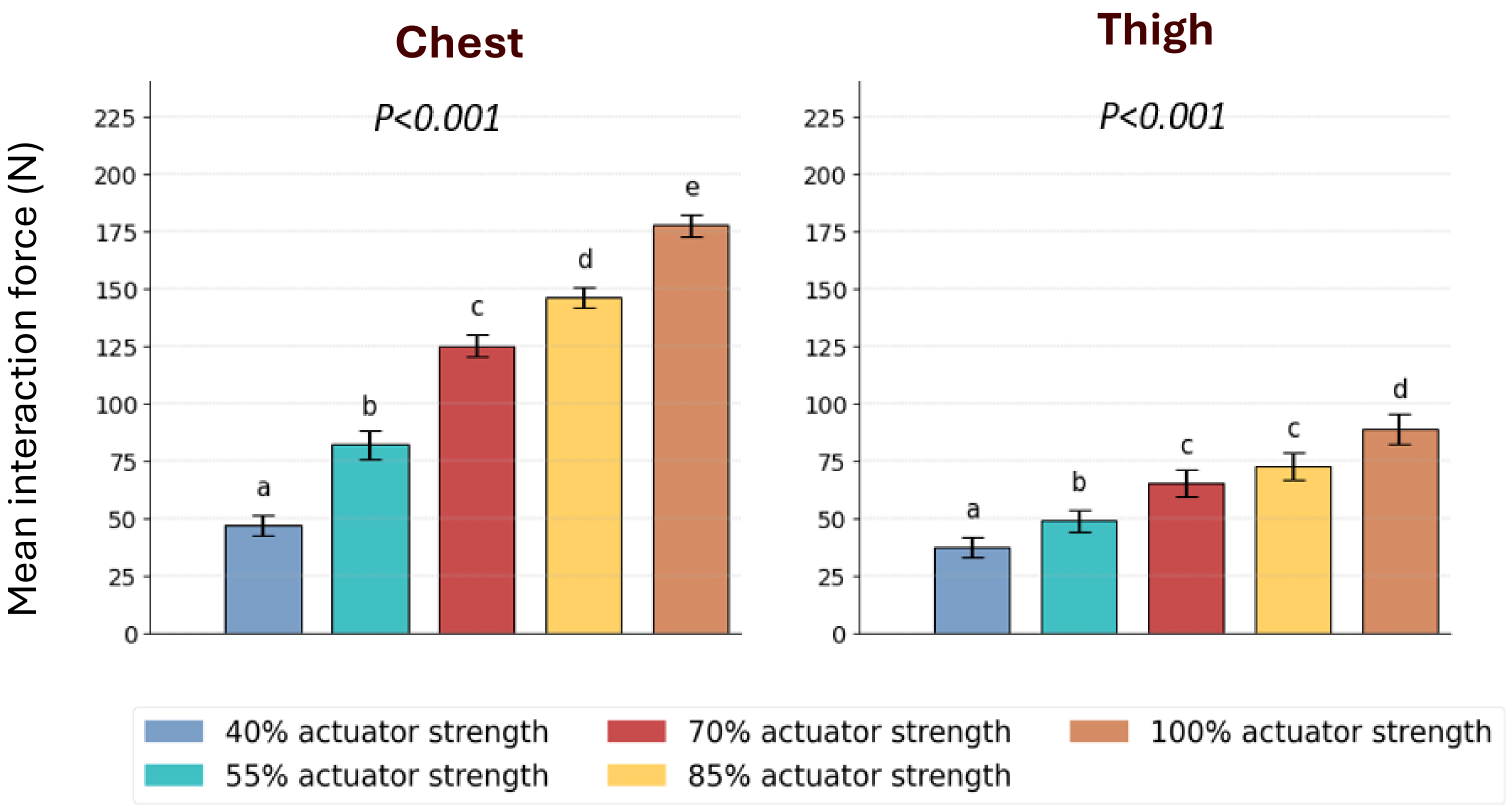
Results: L5/S1 reaction forces



❖ Both were significantly reduced with all support levels of the exoskeleton; however, shear force remained higher than the threshold limit with actuator strength less than 55%

[1] Waters et al., 1993, [2] Gallagher & Marras, 2012

Results: Interaction forces on the chest and thigh



Force/pressure tolerance:
Substantial variability among different individuals and body areas

A previous study [1] reported:

- **55 – 296** N for the thigh
- **185 – 290** N for the chest

(First discomfort threshold for males)

❖ Increased significantly as the support level increased

[1] Kozinc et al,. 2021

Take home messages

- **Exoskeletons' torque should be carefully determined per task and user requirements to ensure sufficient support while avoiding potential side effects.**

- **Integrated human–exoskeleton simulations provide a systematic framework for evaluating exoskeletons' torque profiles and for guiding subsequent human experiments by identifying suitable device–task pairings a *priori*.**

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THANK YOU!

Questions?

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