



Exoskeleton & smart suites

Tested in: Building construction - Helsinki Metropolitan Area, Finland

Christian Di Natali, IIT

Industrial Exo & Monitoring Suit

Smart Suit – Smart clothing



StreamEXO – Back Support Exo.



Solution characteristics:

- Combined devices
- Stand alone devices
- IoT connection

Features:

- Monitoring of the worker's activity
- Development of worker's Digital Twins
- Support worker's activities
- Improve worker's performances
- Improve operational efficacy
- Data generation

Industry 5.0 Technologies

Wearable technologies



Internet of Things

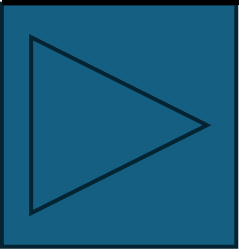


Artificial Intelligence



StreamEXO

- it is an **active back exoskeleton**
- Designed to **assist construction workers** in heavy manual material handling
- Ergonomic and compliant design for
 - An **excellent wearing comfort**
 - **High freedom of movement** in dynamic activities.
- **Continuous size adjustment system** (patented) allowing compatibility with targeted population (one-size-fit-all).
- **Personalized control strategy** adaptable to anthropometry and motion patterns.
- It reduce the overload on the back muscles by 35% and the injury risk by up to 55%



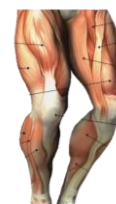
StreamEXO @ Work Sites (TRL6)



Muscular activity reduction

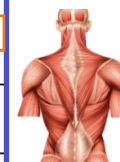
Static Task Assessment

	 Assistance	 Resistance	 Overall
	Erector Spinae		
	StreamEXO	StreamEXO	StreamEXO
Full task	20.89 %	0.94 %	19.95 %
Bending	17.97 %	0.38 %	17.59 %
Position holding	37.21 %	0.00 %	37.21 %
Rising up	14.69 %	2.28 %	12.41 %
	Biceps Femoris		
	StreamEXO	StreamEXO	StreamEXO
Full task	24.91 %	1.00 %	23.91 %
Bending	12.04 %	2.46 %	9.59 %
Position holding	48.92 %	0.00 %	48.92 %
Rising up	18.91 %	0.00 %	18.91 %
	Rectus Femoris		
	StreamEXO	StreamEXO	StreamEXO
Full task	7.65 %	0.09 %	7.56 %
Bending	10.84 %	0.00 %	10.84 %
Position holding	5.16 %	0.00 %	5.16 %
Rising up	4.90 %	0.46 %	4.43 %



Dynamic Task Assessment

	 Assistance	 Resistance	 Overall
	Erector Spinae		
	StreamEXO	StreamEXO	StreamEXO
Lifting	20.99 %	0.00 %	20.99 %
Lowering	20.20 %	0.00 %	20.20 %
	Biceps Femoris		
	StreamEXO	StreamEXO	StreamEXO
Lifting	13.07 %	2.30 %	10.77 %
Lowering	16.25 %	14.22 %	2.03 %
	Rectus Femoris		
	StreamEXO	StreamEXO	StreamEXO
Lifting	9.64 %	0.66 %	8.98 %
Lowering	7.48 %	9.04 %	-1.55 %



Highlights: 37% back muscle reduction in static task, 20% back muscle reduction in dynamic tasks

Reference: Fanti, V., Leggieri, S., Poliero, T., Sposito, M., Caldwell, D.G. and Di Natali, C., 2024. Multi-Exoskeleton Performance Evaluation: Integrated Muscle Energy Indices to Determine the Quality and Quantity of Assistance. Bioengineering, 11(12), p.1231.

Ergonomic Risk reduction (1/3)

Experimental protocol:

15 subjects tested on hoisting test lifting 5 kg and 10 kg in 8 repetitions of three different lifting heights (H1, H2, H3).

Kinect system to assess NIOSH LI analysis, combined with Equivalent Weight method

Weight (kg)	1st Peaking/Releasing Heights	2nd Peaking/Releasing Heights	3rd Peaking/Releasing Heights	4th Peaking/Releasing Heights
5	H1-H2	H2-H2	H3-H1	H2-H3
10	H1-H2	H2-H3	H2-H1	H3-H2

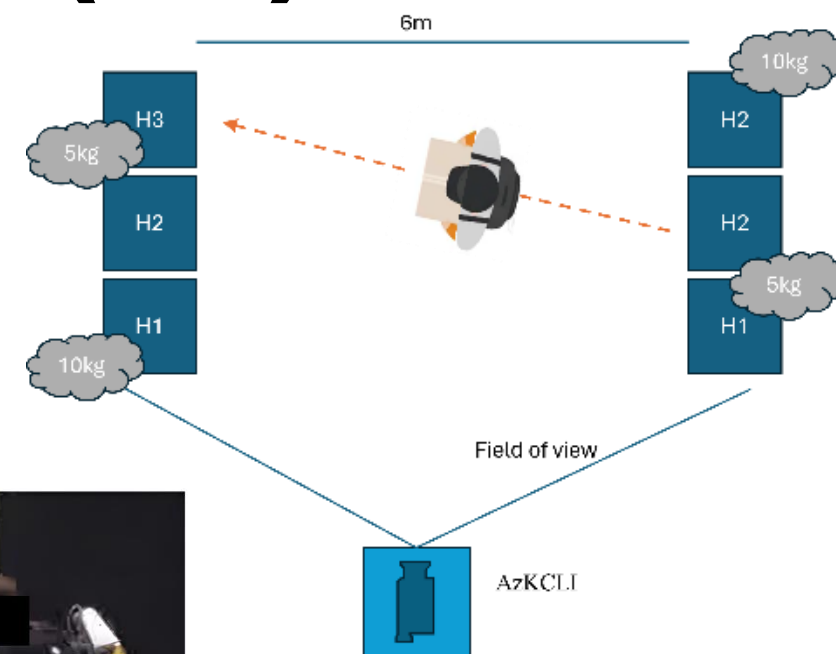


Figure 3.
Experimental protocol

Ergonomic Risk reduction (2/3)

Equivalent Weight (EqW)

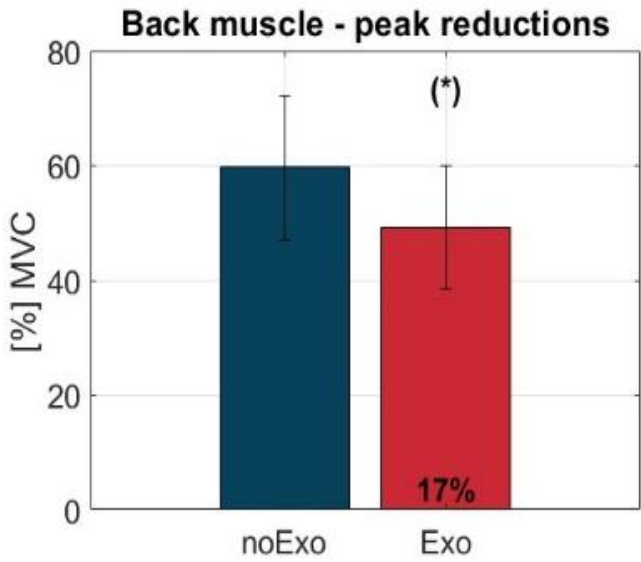
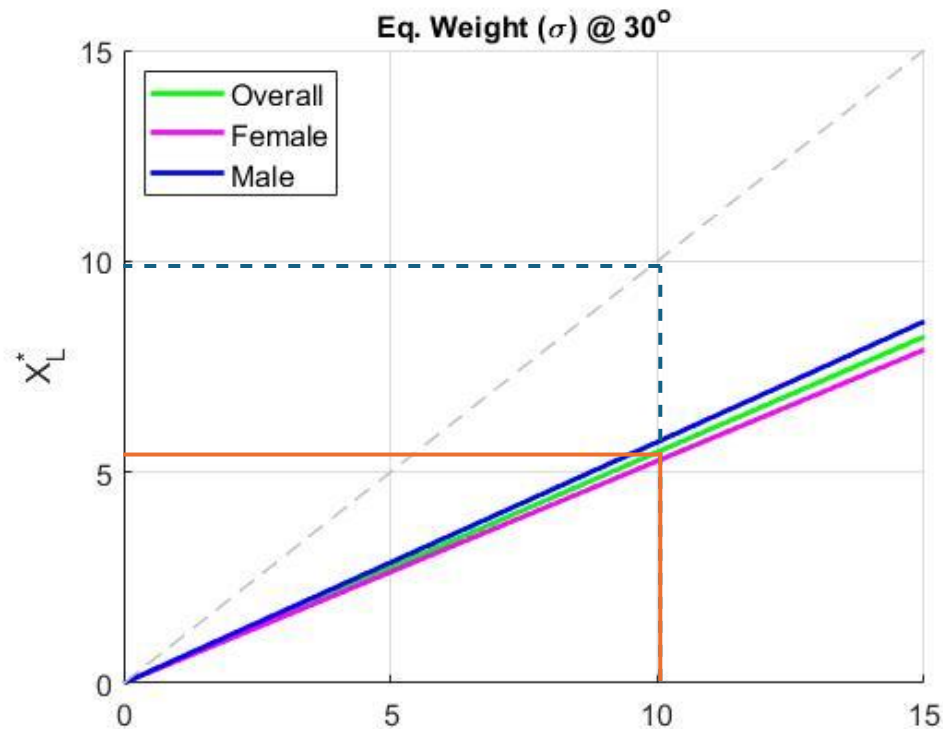


Figure 4. Muscle activity for NOE and EXO. (*) Statistical significance ($p < .05$).

Task	NOE [%MVC]	EXO [%MVC]	ES reduction [%]	EqW σ [%]
Lifting/Lowering	59.71±12.61	49.23±10.83	17.07	82.4

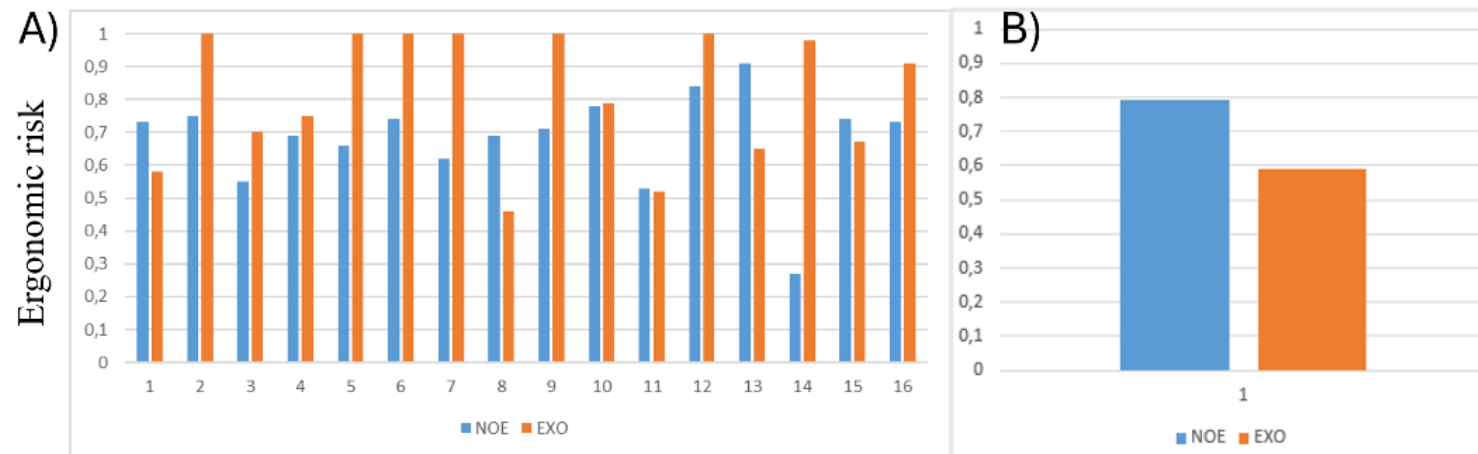
Reduction of 17,1% → 10kg are perceived as 8.2kg

Di Natali, C., et al. "Pilot Test to Evaluate Ergonomic Risk of Industrial Exoskeleton with Semi-autonomous Method that Relies on AzKCLI and the Equivalent Weight." *European Robotics Forum*. Cham: Springer Nature Switzerland, 2025.

Ergonomic Risk reduction (3/3)

Results:

1. Muscle activity reduction
2. EqW
3. Ergonomic assessment



Results:

- Perceived weight reduction of 82.4%
- 10% reduction in postural associated ergonomic risk:

→ Overall, the NIOSH CLI is reduced by 34%

Reference: Christian Di Natali, S. Leggieri, V. Fanti, C. Forgione, A. M. Coruzzolo, F. Lolli, and D. G. Caldwell. 'Pilot test to evaluate Ergonomic risk of industrial Exoskeleton with semi-autonomous method that relies on AzKCLI and the Equivalent Weight.' European Robotics Forum, 2025

Smart Clothing

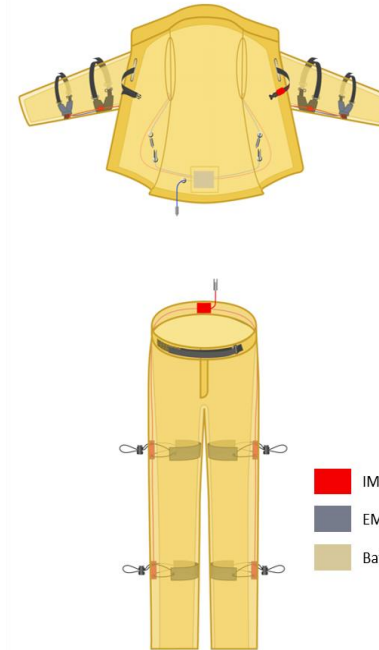
Smart Suit



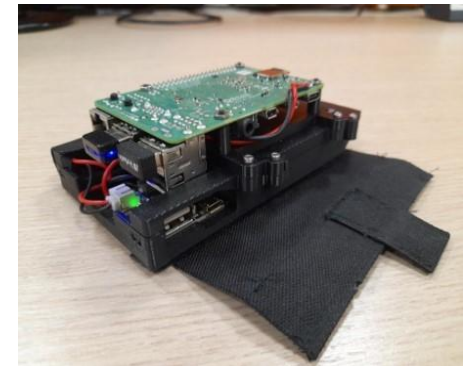
Smart Suit: features

Smart Suit (SS) features:

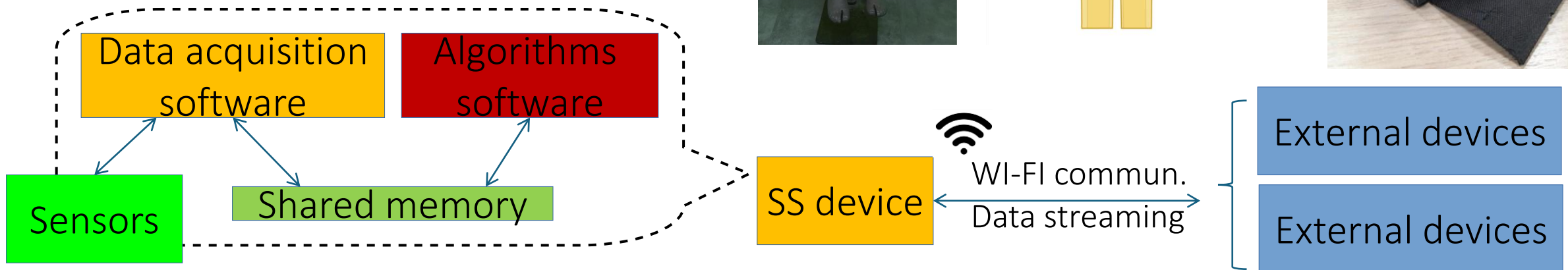
- 2 versions: Lower-body (LB-SS) and Total-body (TB-SS)
- 10 IMUs shanks, thighs, arms, forearms, belt and sternum
- 2 Forearm EMGs
- Breathing frequency sensor



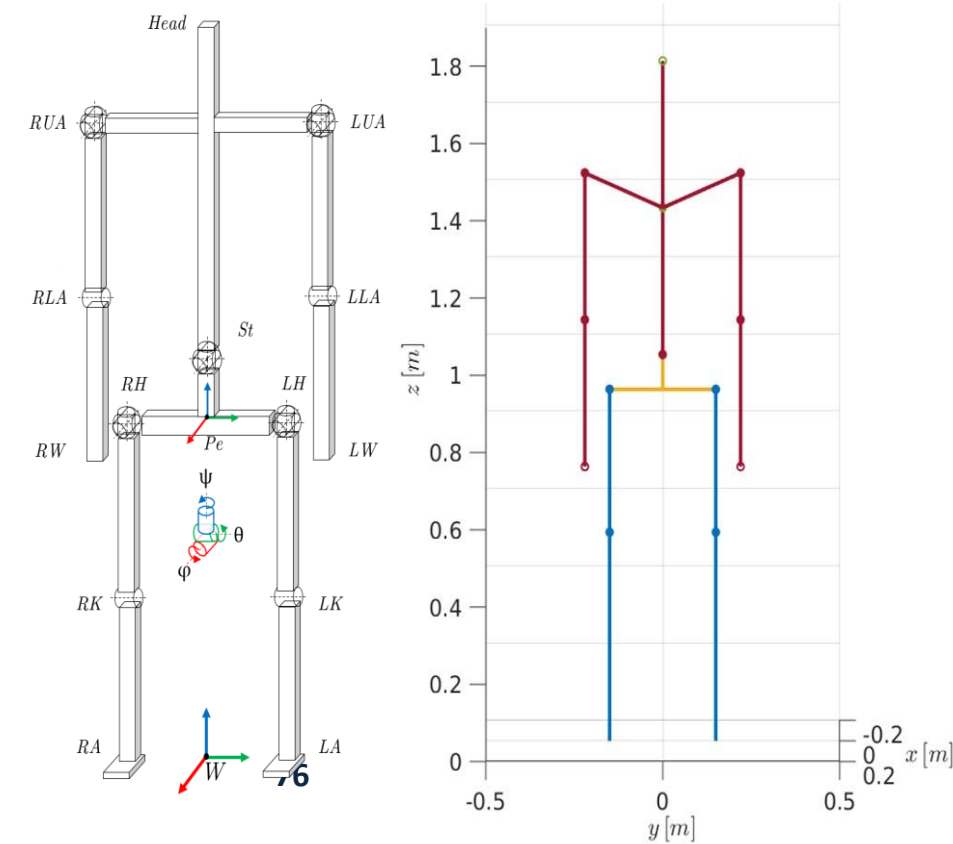
(b)



Smart Suit software integration



Smart Suit: Kinematic reconstruction

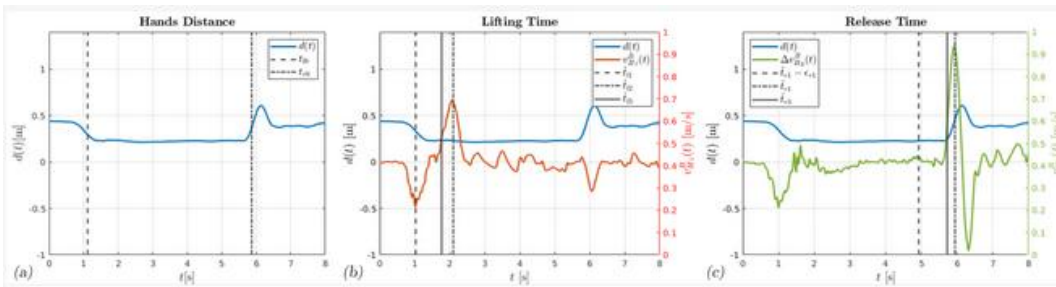
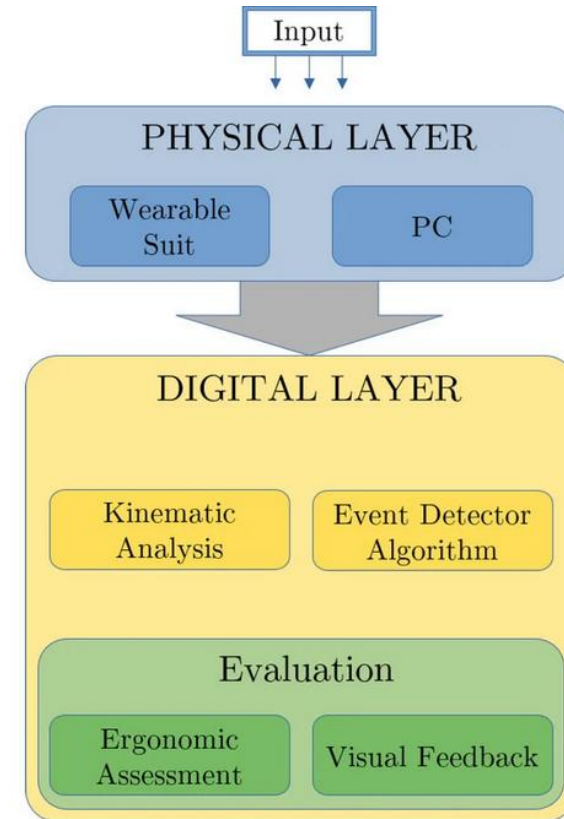
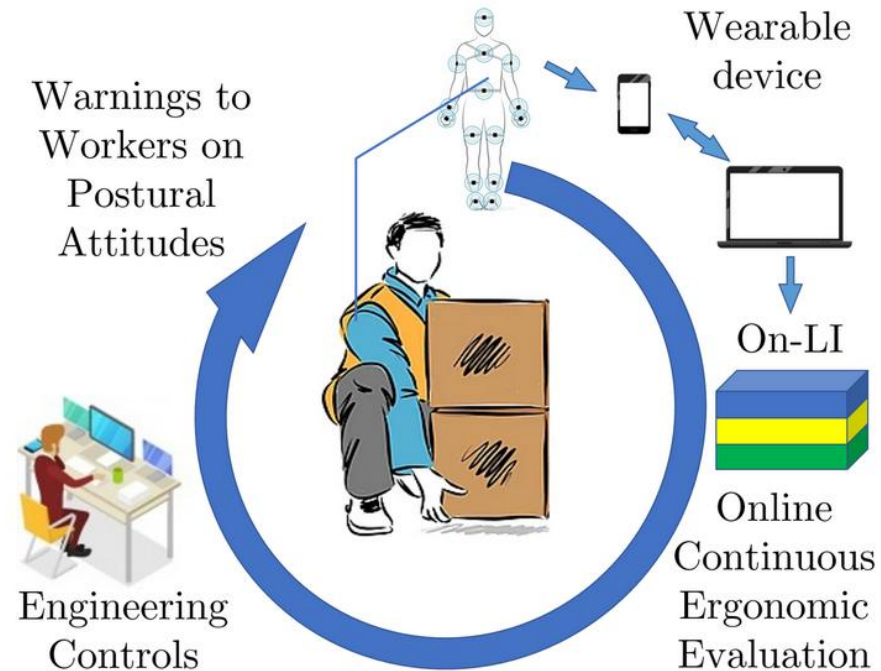


The angles $\Phi = [\phi \ \theta \ \psi]^T$ are the RPY angles that represent the absolute pelvis orientation.
The joint vector $q(t) \in \mathbb{R}^{22}$, is provided by the IMUs angles $q_i(t)$ of each i -th DoF of the model.

Smart Suit: Ergonomic risk assessment

Online Lifting Index (On-LI)

- Online ergonomic evaluations of the NIOSH Lifting Index (LI)
- To improve working conditions
- The algorithm provide online processing and evaluation:
 - The kinematic analysis,
 - The event detector algorithm
 - The NIOSH evaluation.

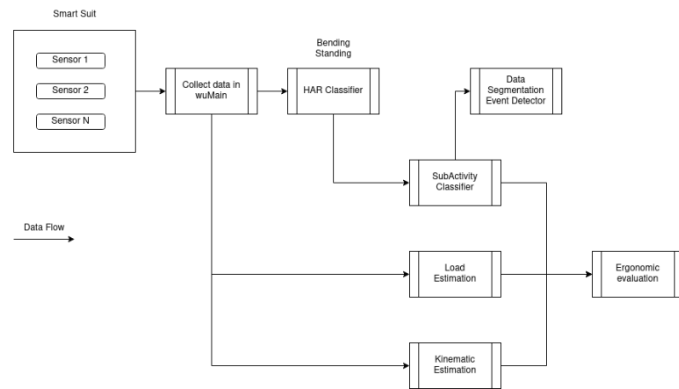


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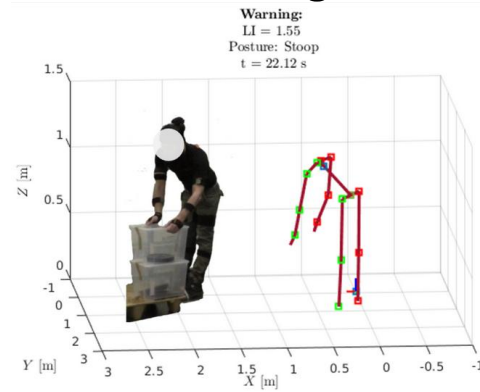
Leggieri, Sergio, Vasco Fanti, Darwin G. Caldwell, and **Christian Di Natali**. "Online Ergonomic Evaluation in Realistic Manual Material Handling Task: Proof of Concept." *Bioengineering* 11, no. 1 (2023): 14.

Smart Suit: Ergonomic risk assessment

Biomechanical Model and RT Algorithm



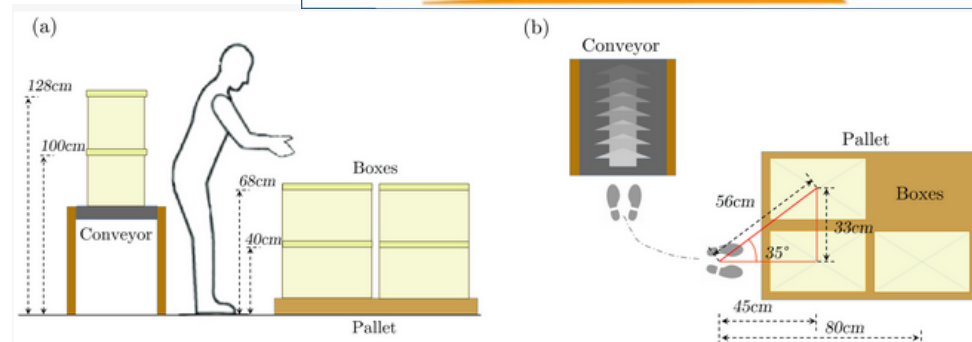
Worker's Digital Twin



Risk based on UNI ISO 11228-1_2022

Lifting Index	Risk Magnitude	Recommendation
≤ 1.00	Very Low	No modification required
1.01 - 1.50	Low	Pay attention to frequency of execution, excessively heavy loads, and/or incongruous postures held too long
1.51 - 2.00	Moderate	Redesign tasks and workplaces according to priorities to reduce the Lifting Index
2.01 - 3.00	High	It is highly necessary to modify the task to reduce the Lifting Index
> 3.00	Very High	It is critically important to change the task immediately to reduce the Lifting Index

Experimental protocol



Leggieri, Sergio, Vasco Fanti, Darwin G. Caldwell, and Christian Di Natali. "Online Ergonomic Evaluation in Realistic Manual Material Handling Task: Proof of Concept." *Bioengineering* 11, no. 1 (2023): 14.



Fatigue Trend Analysis with Smart Wearables

Janne Keränen, VTT

Fatigue Trend Analysis

- The Fatigue Trend Analysis technology is incorporated in the BEEYONDERS Building Construction use case, where among other things, smart wearable sensors are used to measure occupational health and safety variables.
- A major proportion of injuries in the construction industry are due to physical overexertion [1]. Physical load of work and fatigue are critical challenges workers face in everyday work, and additional means are needed for their early identification and management to prevent long-term consequences at workplaces.
- Fatigue Trend Analysis uses data from small inertial measurement units (IMU). IMUs present benefits: IMU sensors are cheap, they can be easily integrated into clothing, and they are unobtrusive.

[1] <https://www.insst.es/documents/94886/96076/DT+81-1-13+riesgos+emergentes+meta.pdf>

Fatigue Trend Analysis

- In BEEYONDERS, Fatigue Trend Analysis has been used to assess data from the Smart Suit developed by IIT [2]. The data was from workers performing simulated work activities at a real building construction site in Helsinki, Finland.
- With this data, Fatigue Trend Analysis was able to estimate the levels of used effort throughout the work.
- Fatigue Trend Analysis can be used to assess further smart wearables data to predict and assess fatigue levels of construction site workers.
- The overall societal goal is to improve workers' wellbeing by developing fatigue monitoring solutions that are deployable in real working context.

[2] Leggieri, S.; Sencandan, P.; Fanti, V.; Ahmad, J.; Caldwell, D. G.; Di Natali, C. The Smart Suit: a novel tool platform for learning and assessment at work, 5th IFSA Winter Conference on Automation, Robotics & Communications for Industry 4.0/5.0 (ARCI' 2025) 19-21 February 2025, Granada, Spain