Kinematics-Based Adaptive Assistance of a Semi-Passive Upper-Limb Exoskeleton for Workers in Static and Dynamic Tasks

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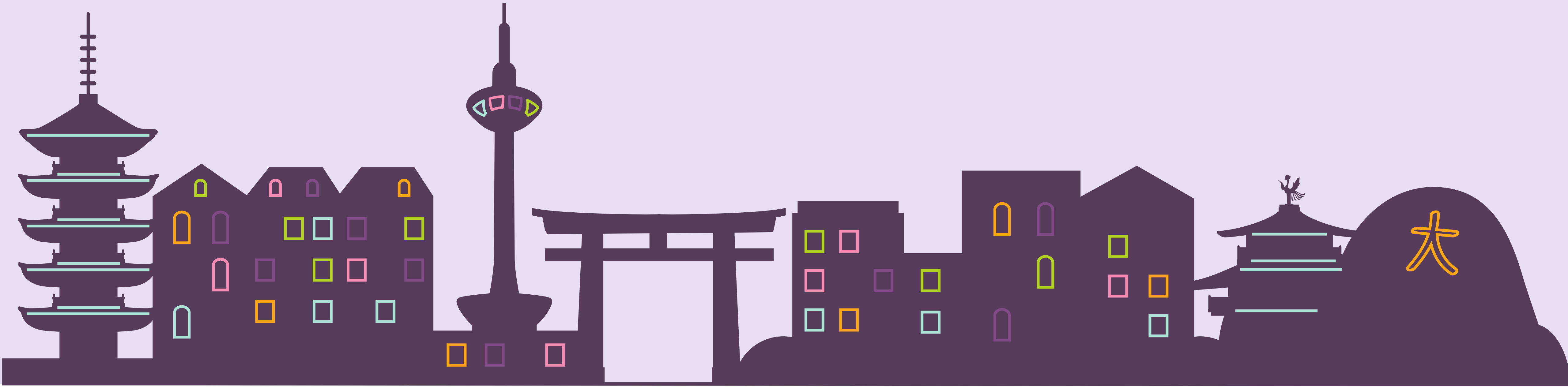


Background and motivations

Passive occupational exoskeletons and their limitations

Passive occupational exoskeletons

Scientific literature is rich in examples of passive **occupational exoskeletons**, aiming at:

- reducing muscular strain and global body fatigue
- reducing the occurrence of work-related musculoskeletal disorders, e.g., shoulder impingement syndrome or rotator cuff tendinopathies
- potentially reducing the ergonomic risks related to specific work activities

They usually rely on elastic elements to store and release energy and to provide the user with antigravitational support.




The need for adaptive control

Occupational upper-limb exoskeletons can assist the shoulder complex in both static and dynamic gestures

...but...

in passive devices, the amount of assistance is manually regulated by the user, and it **cannot adapt** to the high variability of typical work tasks:

- task pace and intensity
- working posture
- use of tools of different weights

or worker's physical conditions:

- increased biomechanical load on human joints
- increased muscular effort
- increased fatigue

New technological solution

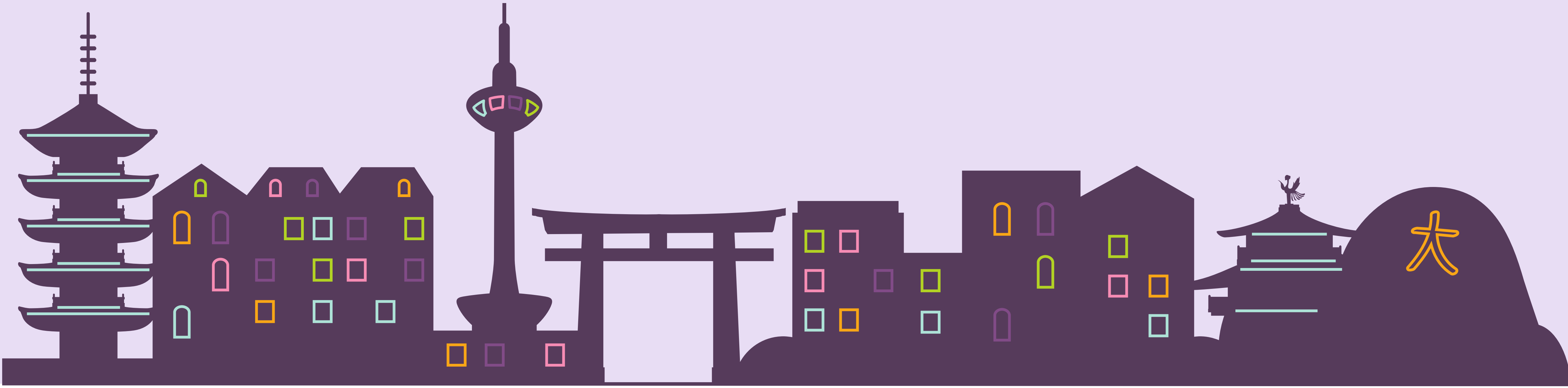
- To tackle the limitation of passive devices, semi-passive (or semi-active) exoskeletons have been developed [3].
- Semi-passive exoskeletons are devices designed to adapt the passive behavior of the system by:
  - automatically adapting the level of assistance
  - engaging/disengaging the actuation mechanisms through active clutches
- **Adaptation** can be achieved through observation of the task being performed, the user's stress level, or other context-related factors.

[1] S. Crea et al., "Occupational exoskeletons: A roadmap toward large-scale adoption. Methodology and challenges of bringing exoskeletons to workplaces," Wearable Technol., vol. 2, 2021, doi: 10.1017/wtc.2021.11

Objective of this work

This work presents a **novel adaptive algorithm** aimed at automatically setting the level of assistance, based on kinematic information extracted from joint angle sensors integrated into a semi-passive shoulder exoskeleton, named H-PULSE.

This is the first adaptive algorithm designed for a semi-passive exoskeleton for workers assistance.



The H-PULSE exoskeleton

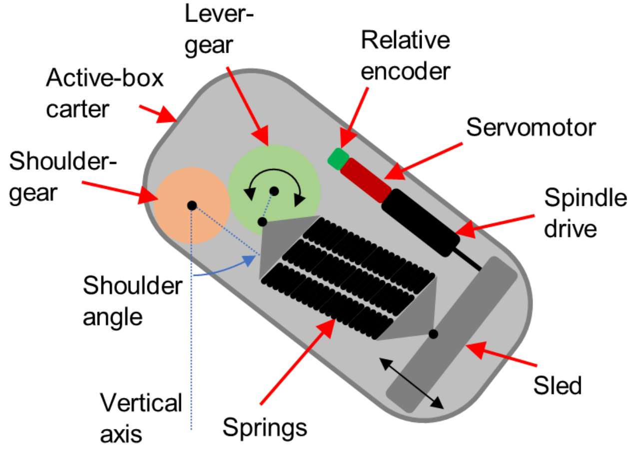
A novel semi-passive exoskeleton for workers assistance

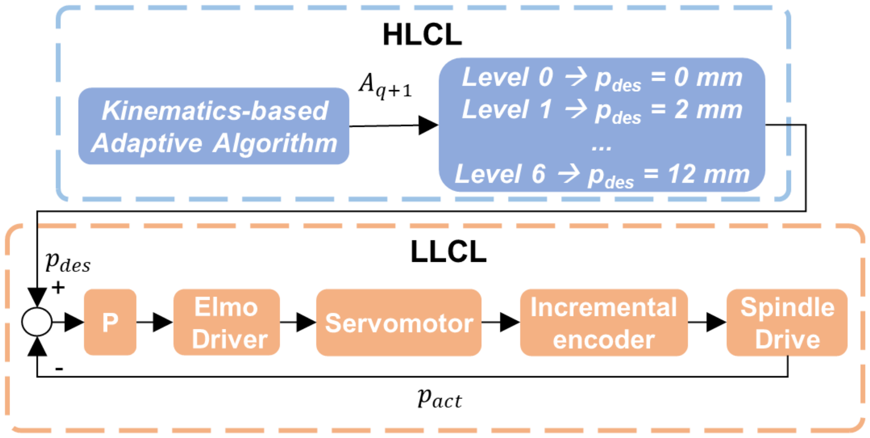
The H-PULSE exoskeleton

Designed by IUVO S.r.l. (Pontedera, Pisa, Italy), spin-off company of Scuola Superiore Sant'Anna. The technology is patented [2].

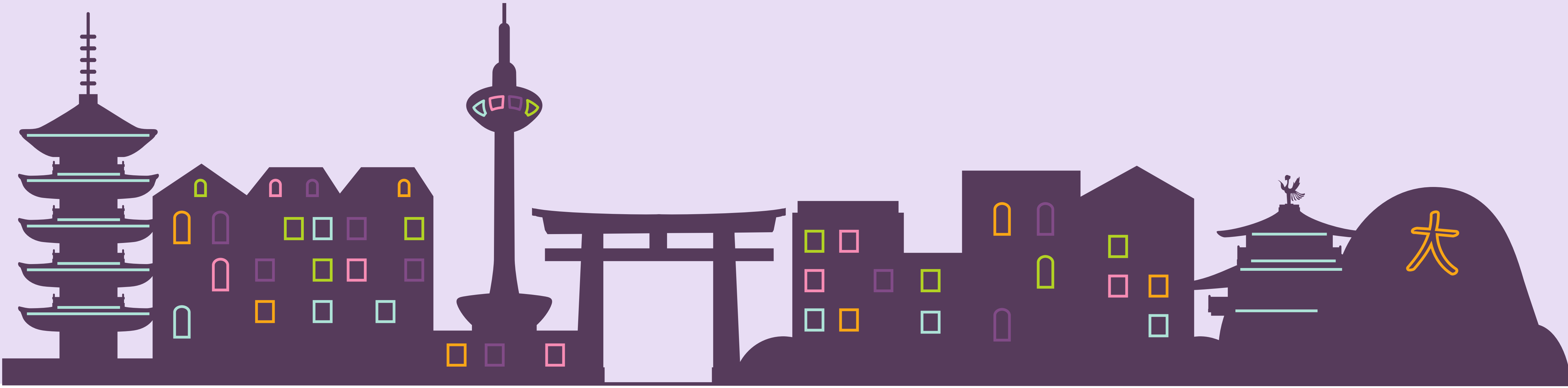
The exoskeleton weighs 5 kg and integrates four main modules [3]:

1. a garment as a physical Human-Robot Interface
2. a chain of passive degrees of freedom (pDOFs)
3. two actuation boxes with a spring-loaded mechanism generating the assistive torque, a servomotor to set the level of the springs' pre-tension, and joint encoders
4. the control unit running on a National Instruments System-on-Module housed in a backpack





[2] F. Giovacchini, M. Moisè, G. Proface, L. Morelli, and N. Vitiello, "System for assisting an operator in exerting efforts," US Patent US2022/0161415A1, 2022
[3] L. Grazi, E. Trigili, G. Proface, F. Giovacchini, S. Crea, and N. Vitiello, "Design and experimental evaluation of a semi-passive upper-limb exoskeleton for workers with motorized tuning of assistance," IEEE Trans. Neural Syst. Rehabil. Eng., vol. 28, no. 10, pp. 2276–2285, Oct. 2020, doi: 10.1109/tnsre.2020.3014408.



Hypotheses

Grounded on biomechanical assumptions

Main hypotheses

The hypotheses behind the design of the kinematics-based adaptive algorithm are grounded on biomechanical assumptions.

The objective is to develop a model describing the relationship between the static/dynamic nature of the shoulder flexion/extension (sFE) angle signal and the desired level of assistance to be provided by the exoskeleton.

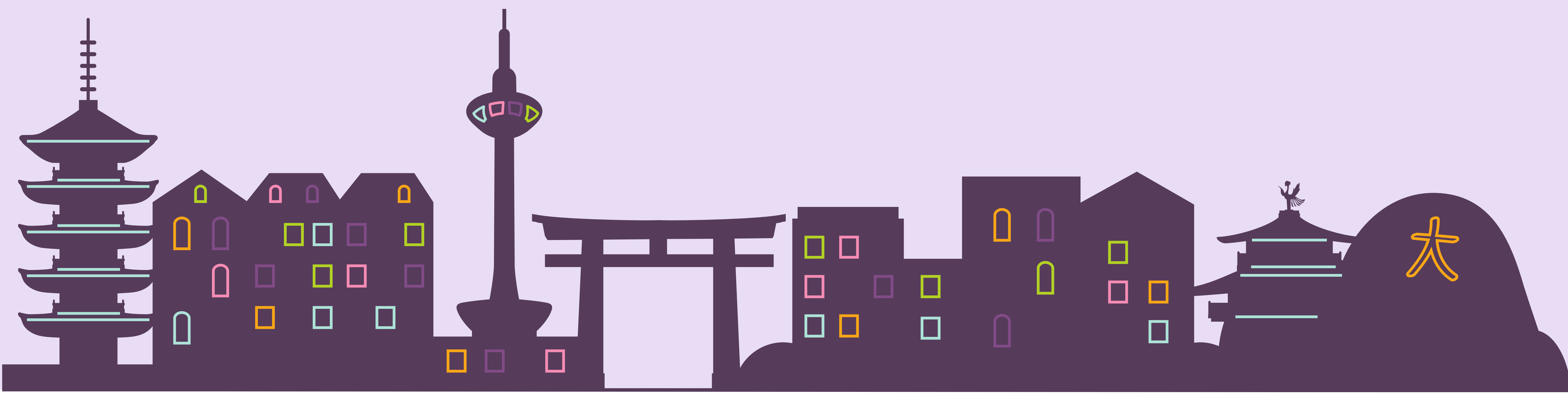
Movement kinematics can be seen as the combined contribution of low- and high-frequency components, namely as the **combination of static and dynamic movements**

Increase with the degree of the static nature of the movement

To support the force exerted by the arm flexors/abductors that mainly contribute to keeping the arms raised, by counterbalancing the arms' gravitational torque at the glenohumeral joint

Decrease as the dynamic characteristics of the movement increase

To support the eccentric work done by the flexor muscles during arms extension and at the same time preventing the action of the antagonistic (extensor) muscles against the device assistance

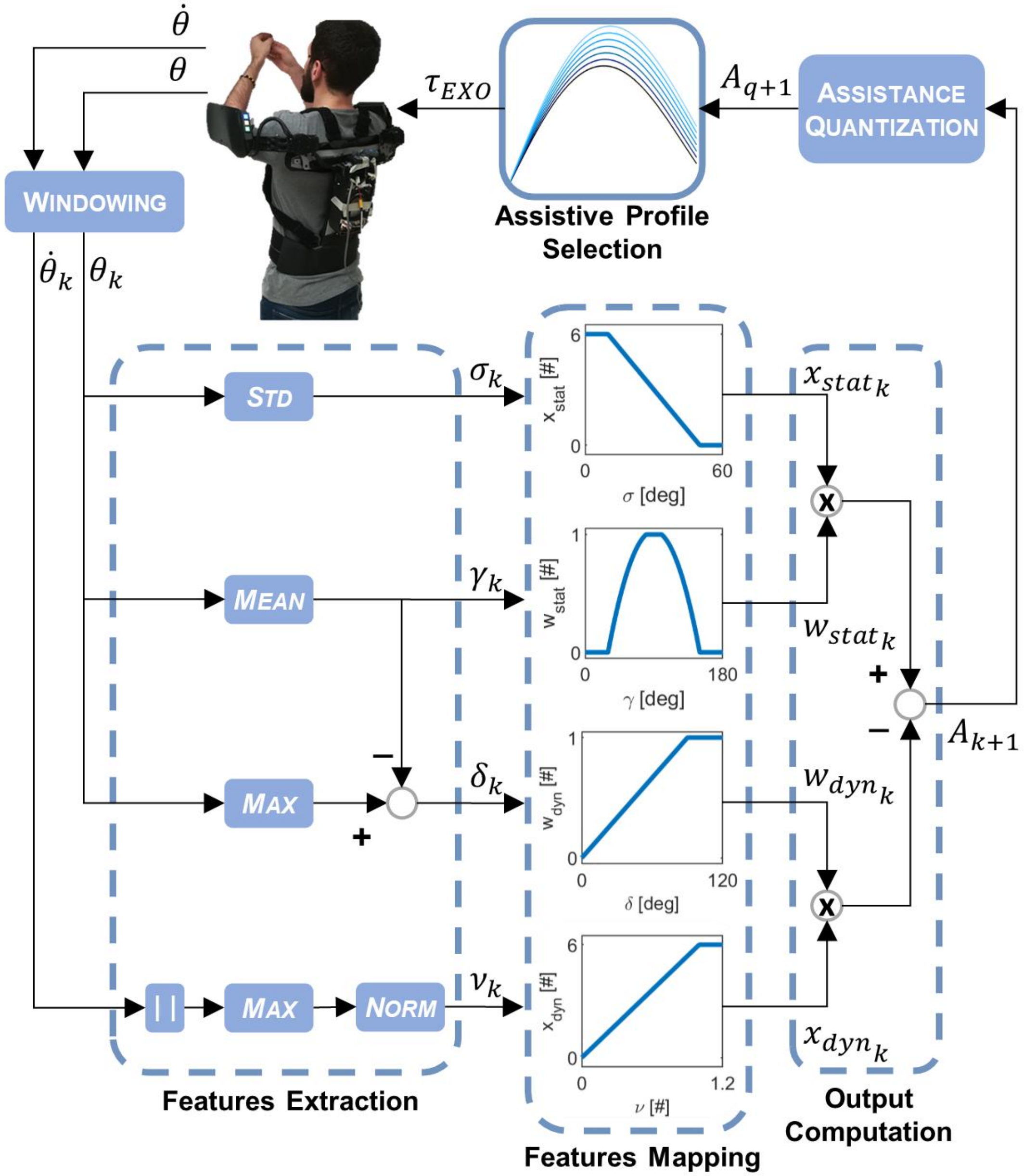


The adaptive algorithm

Design and key features

Adaptive algorithm's building blocks

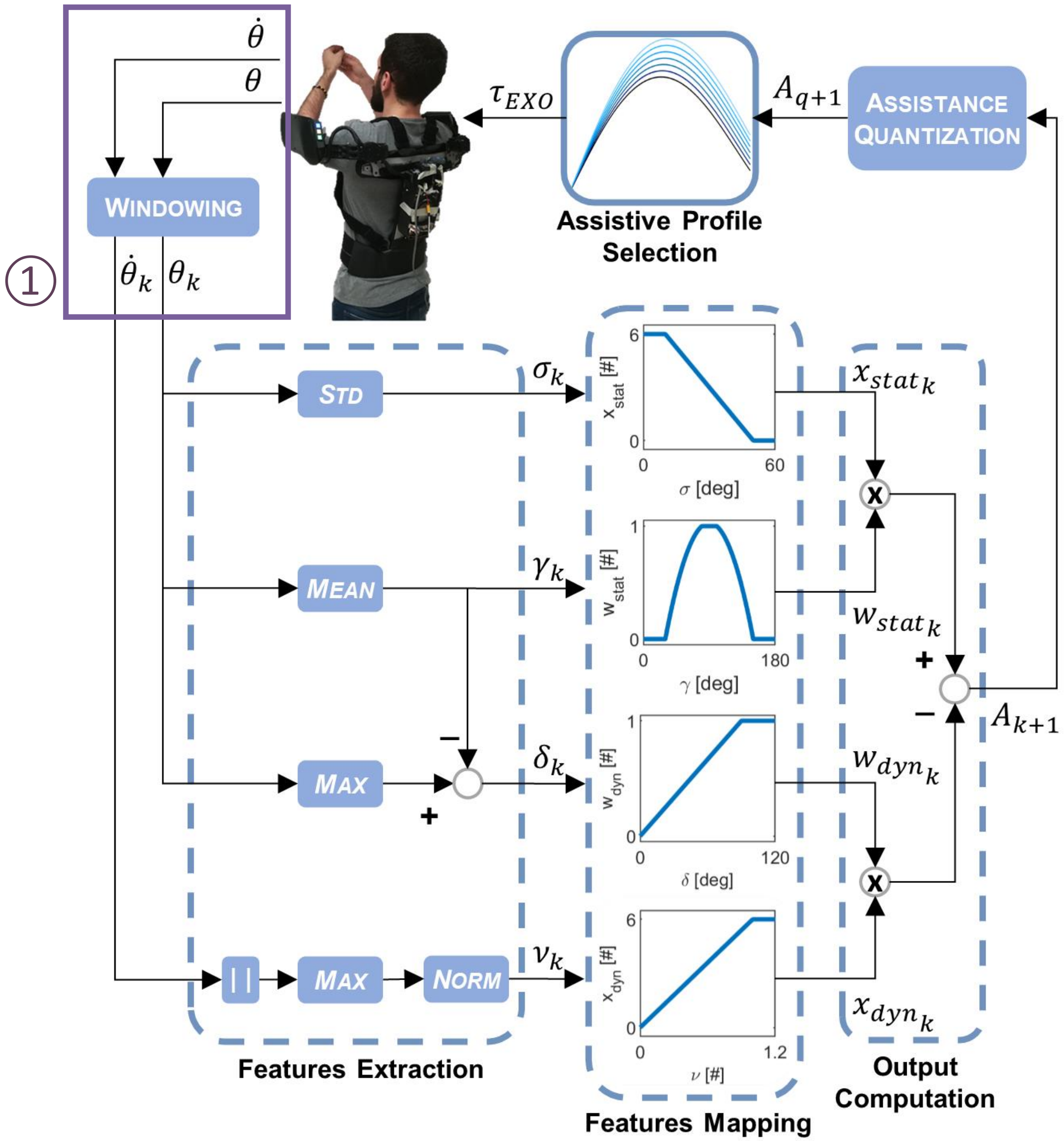
1. Input signal windowing
2. Features extraction
3. Features mapping
4. Output computation
5. Assistance quantization



Adaptive algorithm's building blocks

1. **Input signal windowing**
2. Features extraction
3. Features mapping
4. Output computation
5. Assistance quantization

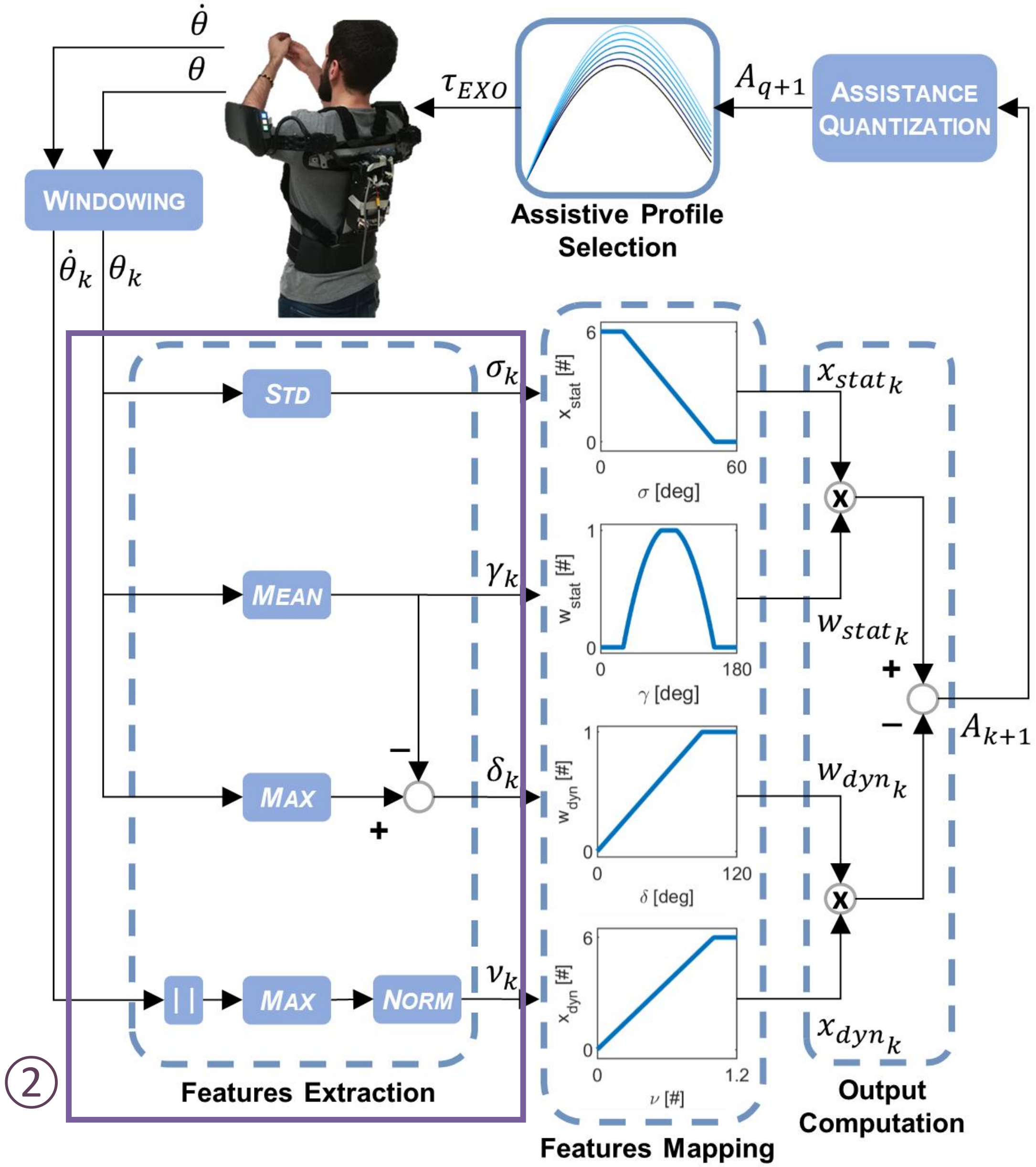
sFE angle and angular velocity are collected in a 6-second non-overlapping virtual buffer.



Adaptive algorithm's building blocks

1. Input signal windowing
2. **Features extraction**
3. Features mapping
4. Output computation
5. Assistance quantization

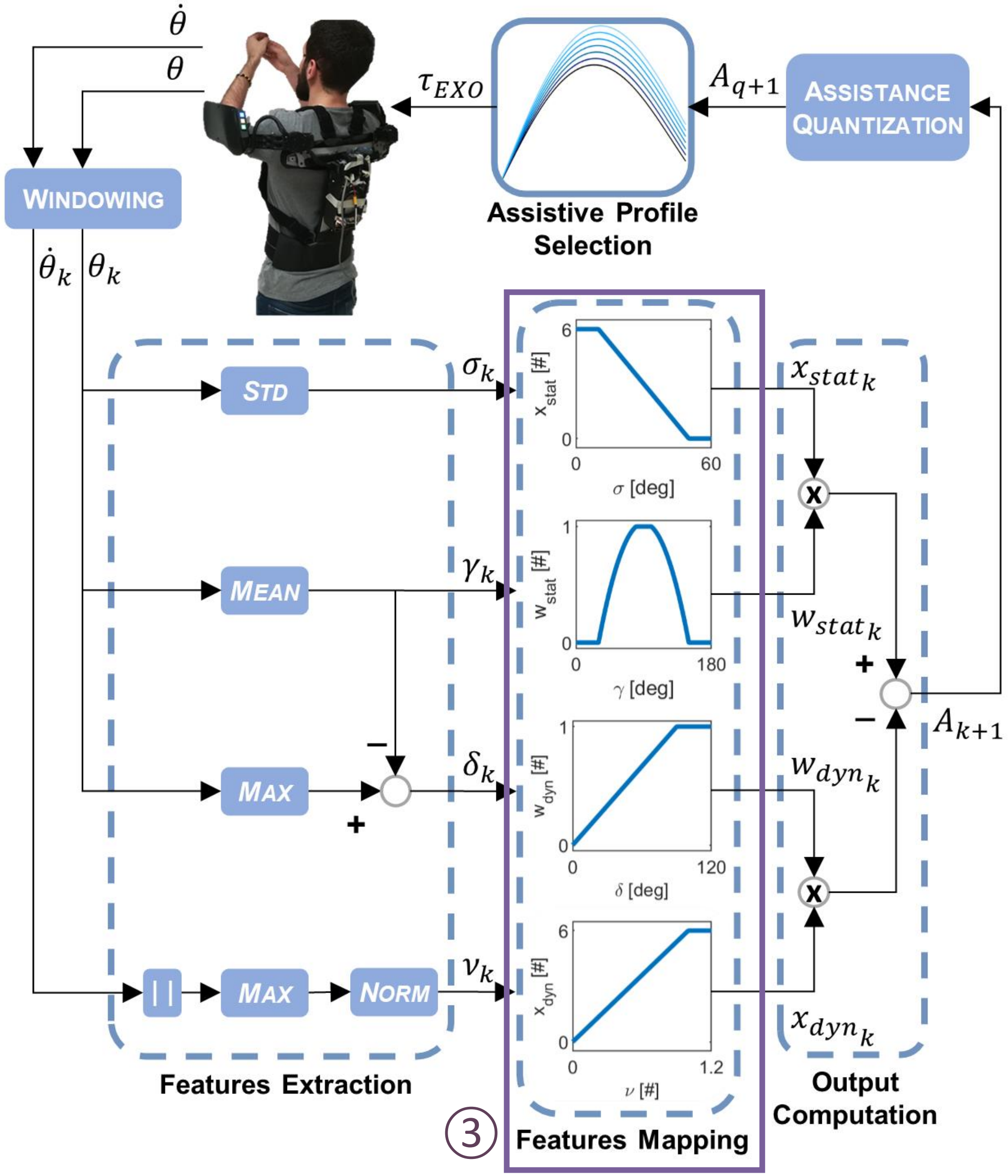
Four features (sFE mean and standard deviation, maximum angular displacement from the mean, normalized maximum velocity) are extracted from the data stored in the virtual buffer.



Adaptive algorithm's building blocks

1. Input signal windowing
2. Features extraction
3. **Features mapping**
4. Output computation
5. Assistance quantization

Features are mapped through membership functions into static and dynamic indices and weights.

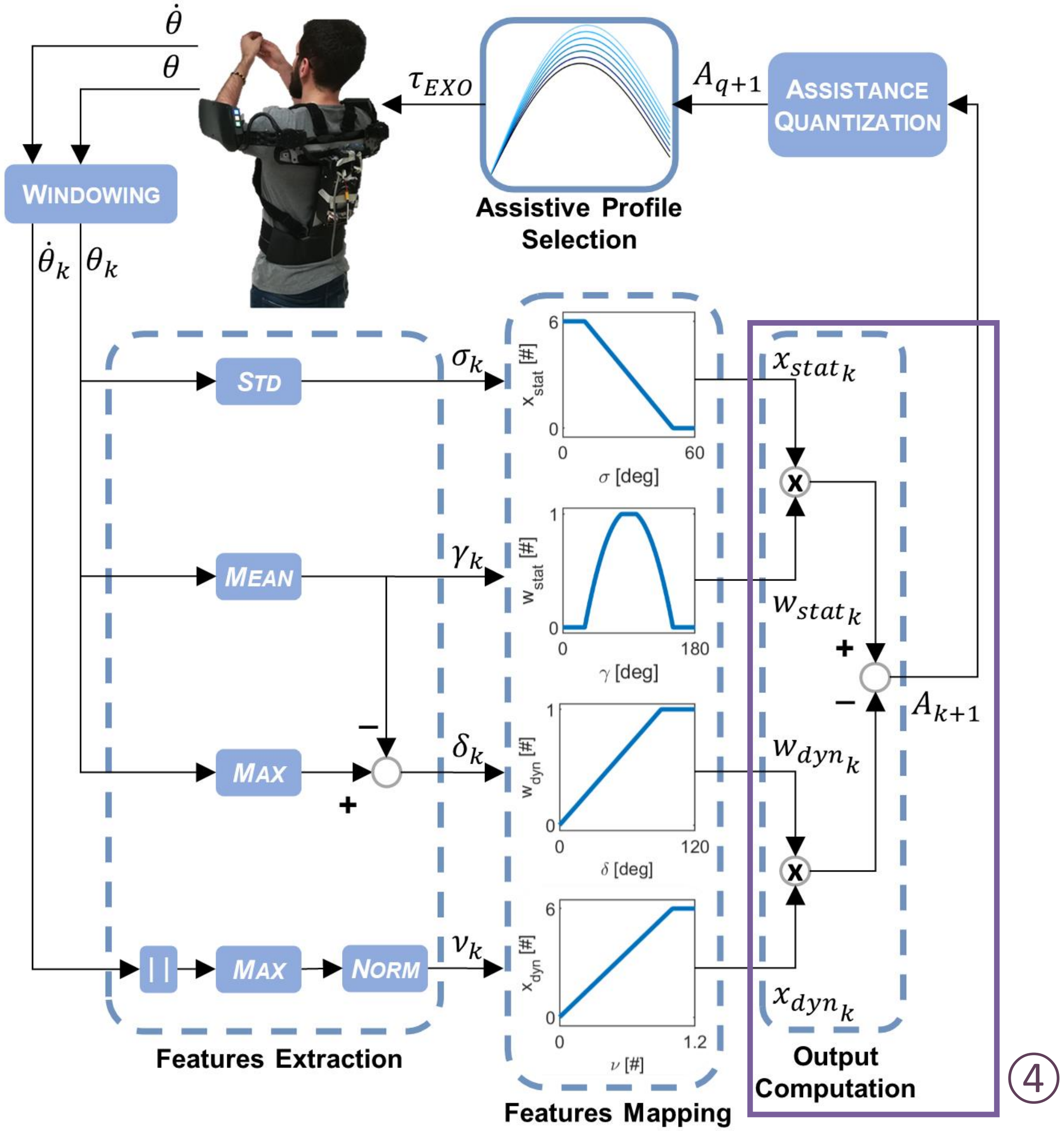


Adaptive algorithm's building blocks

1. Input signal windowing
2. Features extraction
3. Features mapping
4. **Output computation**
5. Assistance quantization

The output of the algorithm (A_{k+1}), computed at the k[th] window, is defined as the linear combination of static and dynamic components:

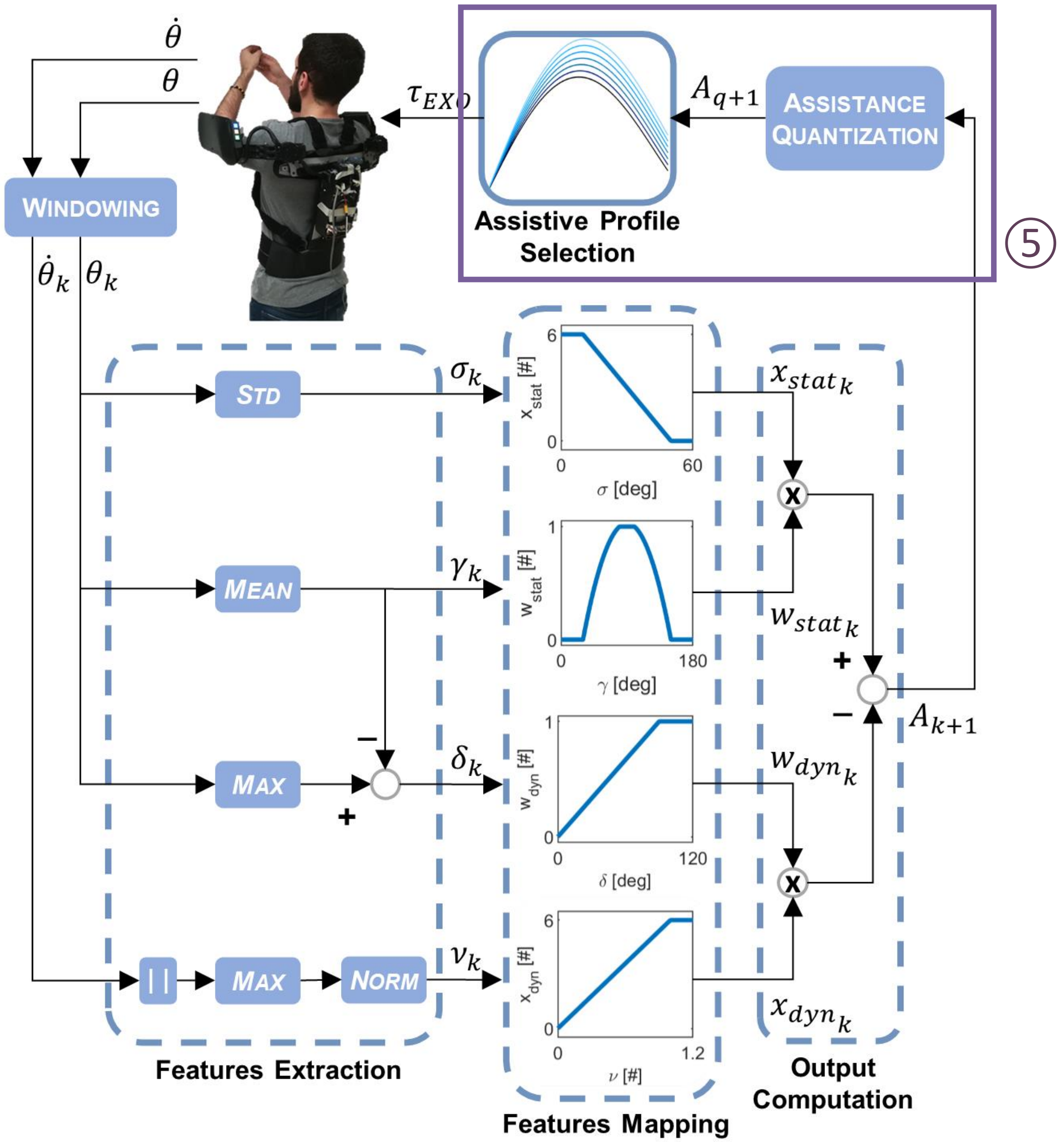
$$A_{k+1} = A_{stat_k}(\gamma_k, \sigma_k) - A_{dyn_k}(\delta_k, \nu_k)$$



Adaptive algorithm's building blocks

1. Input signal windowing
2. Features extraction
3. Features mapping
4. Output computation
5. **Assistance quantization**

A_{k+1} value is quantized to generate a discrete assistance level (A_{q+1}). The corresponding spindle drive position is then commanded to the LLCL.



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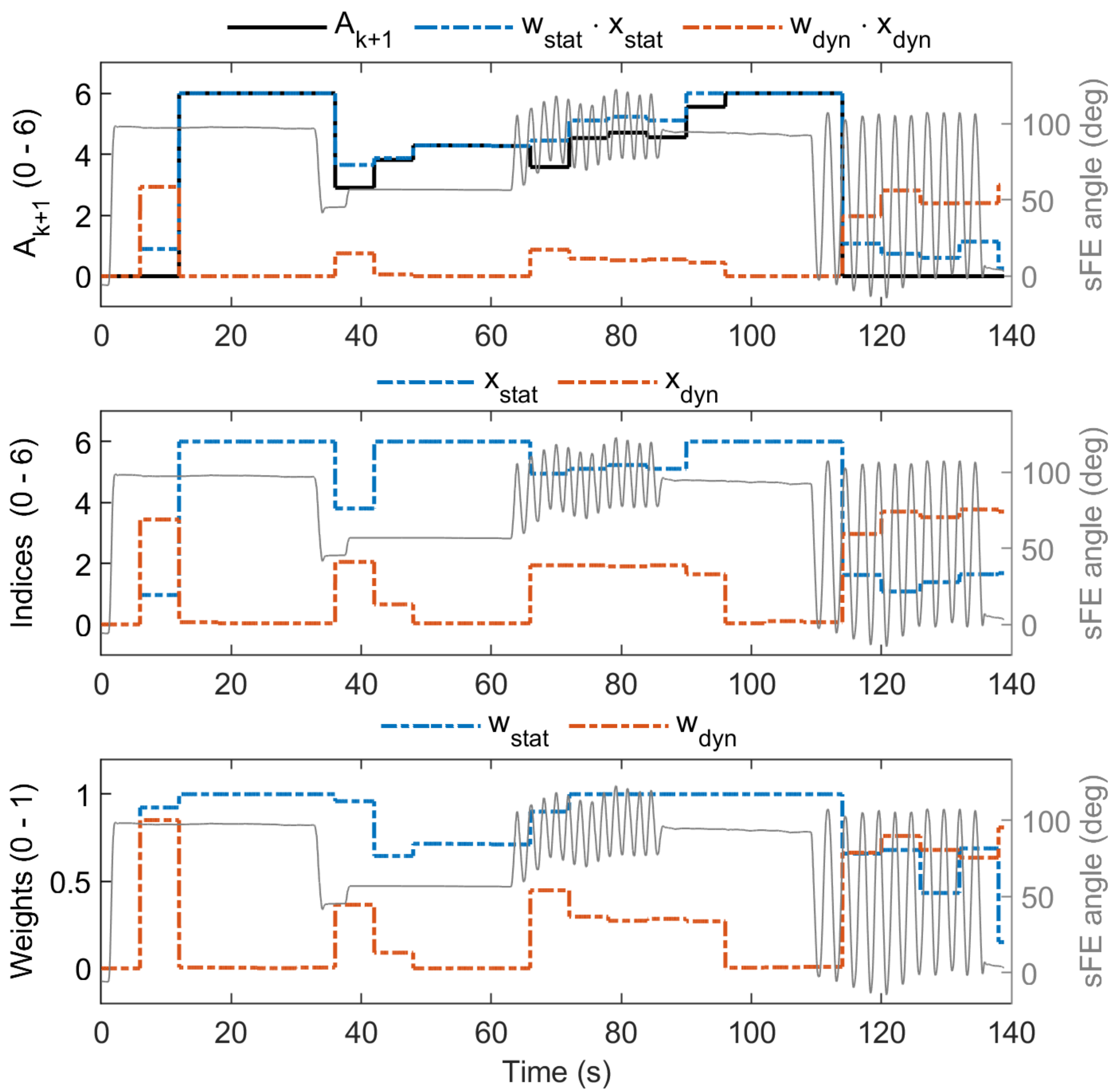
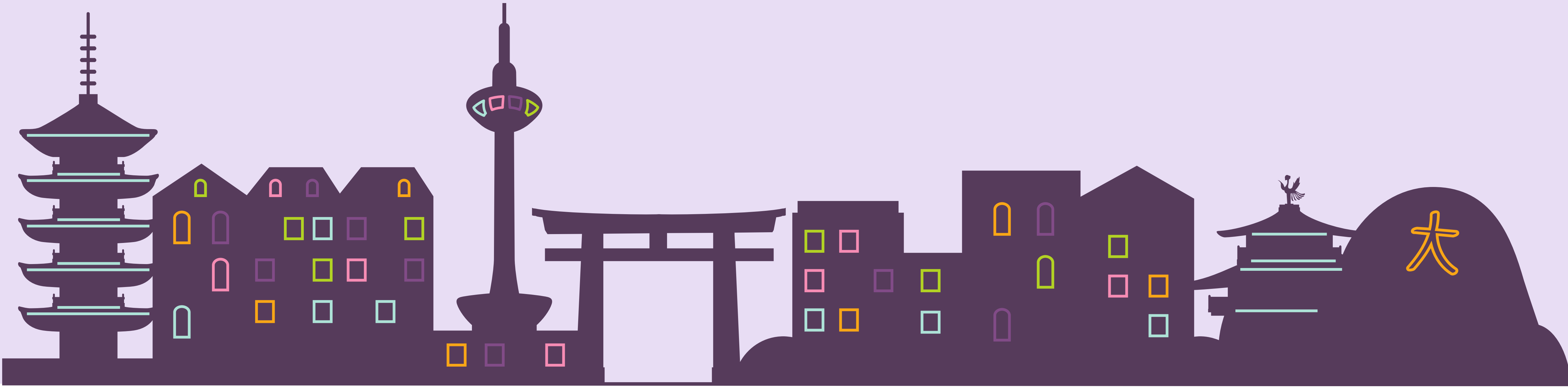
Algorithm's output, indices, and weights

Algorithm's output, indices, and weights computed from an exemplary dataset including a sequence of static and dynamic movements, performed at different shoulder elevation angle and velocity.

Static and dynamic components are complementary to a certain extent.





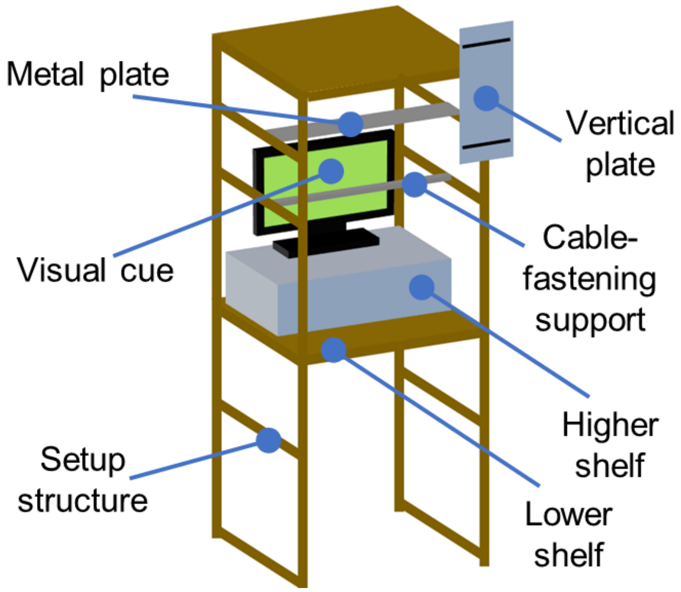
Experimental evaluation

Algorithm’s output characterization and effectiveness assessment

Experimental setup, participants, and tested conditions

Two experimental sessions were carried out to:

1. characterize the algorithm's output **(Session #1)**
2. verify the effectiveness of the proposed assistive strategy on muscles activity **(Session #2)**

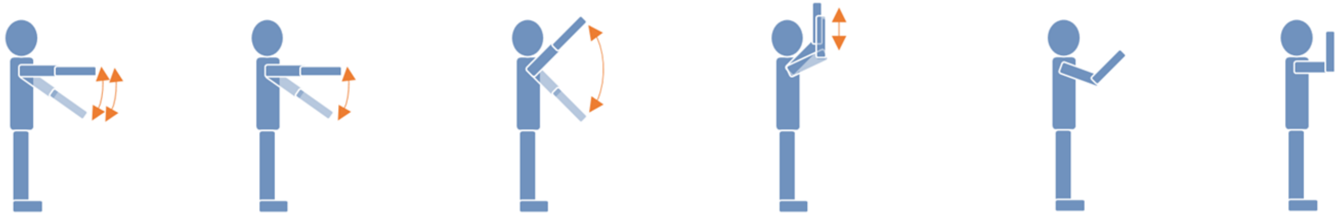


Experimental setup

Tools used

Participants:

- Sessions #1: 10 male subjects (age: 27.7±3.5 years, height: 180.7±6.9 cm, weight: 73.7 ± 10.7 kg)
- Session #2: 6 male subjects (age: 29.1 ± 4.1 years, height: 178 ± 5.4 cm, weight: 70.8 ± 6.4 kg).



Tested conditions

Session #1
Output characterization

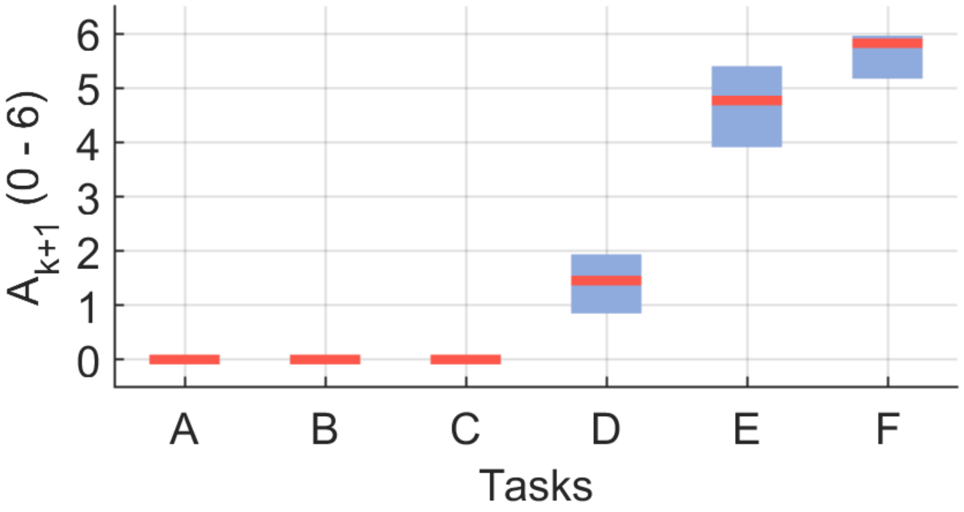
Each subject tested six dyads, each consisting of two consecutive 90-seconds tasks.

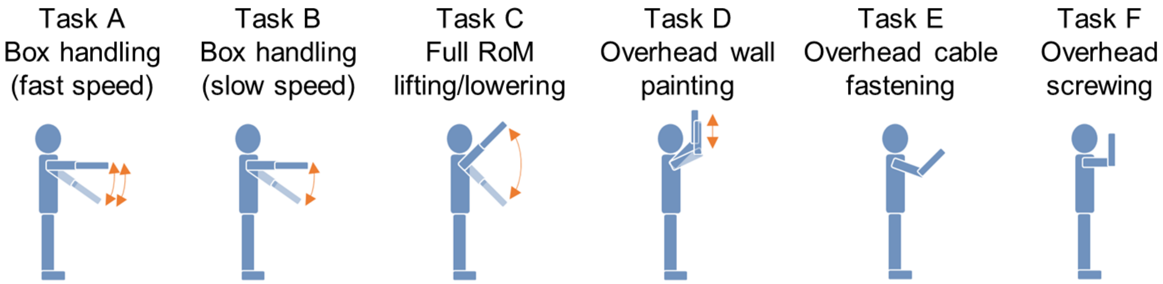
Twenty repetitions per each tasks were collected.

Subjects stood still in front of the setup with arms lying parallel to the body.

The experimenter verbally instructed the subjects on when to start, change, and stop the tasks.

The exoskeleton output the minimum assistance level, and sFE angular data was collected for offline analysis.





Session #2 Effectiveness assessment

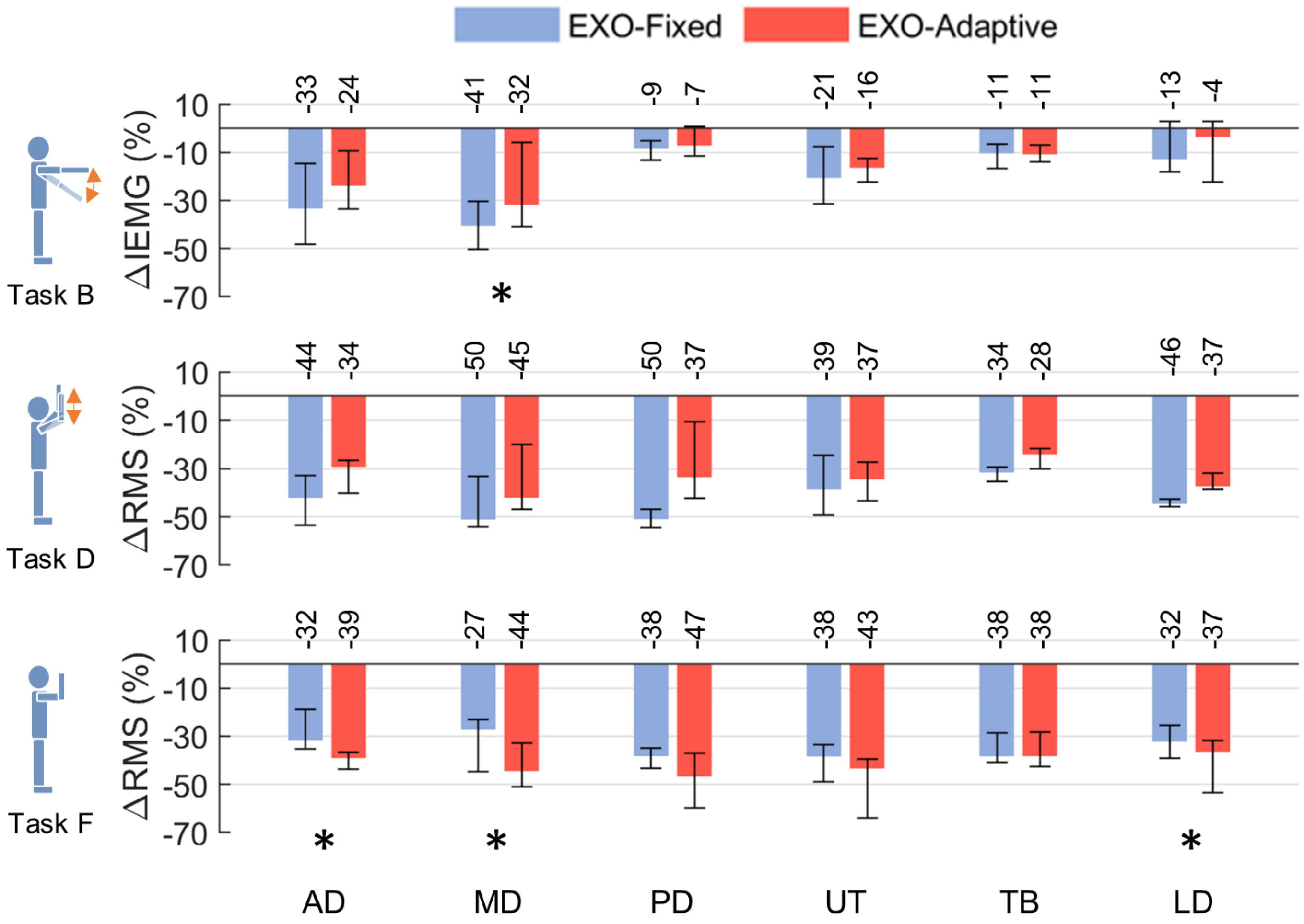
To evaluate the effectiveness of the adaptive algorithm compared to fixed assistance.

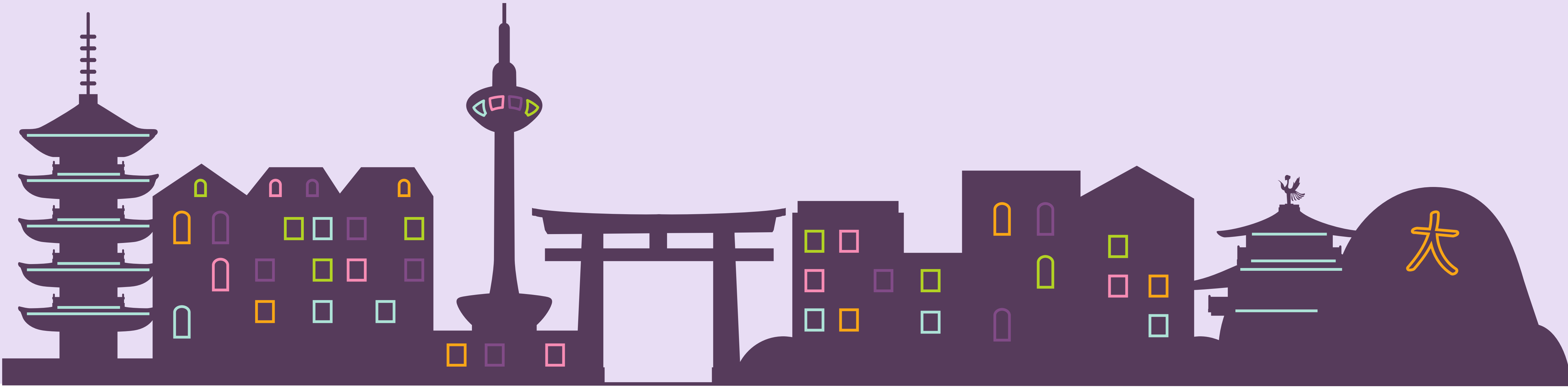
The effectiveness was quantified by EMG measurements on three tasks representative of different levels of dynamic and static contributions.

3 experimental conditions

- NO EXO
- EXO-Fixed (~50% of the arm gravitational torque,)
- EXO-Adaptive (4.5, 4.7, 6 Nm)

Results are shown as percentage variations with respect to the NO EXO condition.





Conclusions and future works

The first proof of concept of adaptive control for semi-passive occupational exoskeletons

Main lessons learned

The algorithm was able to provide different levels of assistance as the level of static/dynamic component of the movement changes

1. This result was in line with the initial design assumptions
2. Algorithm’s output was consistent for all subjects showing robustness to the user’s anthropometric sizes

Regardless of the assistive condition (EXO-Fixed or EXO-Adaptive), the use of the exoskeleton reduced muscles’ physical strain compared to the NO EXO condition

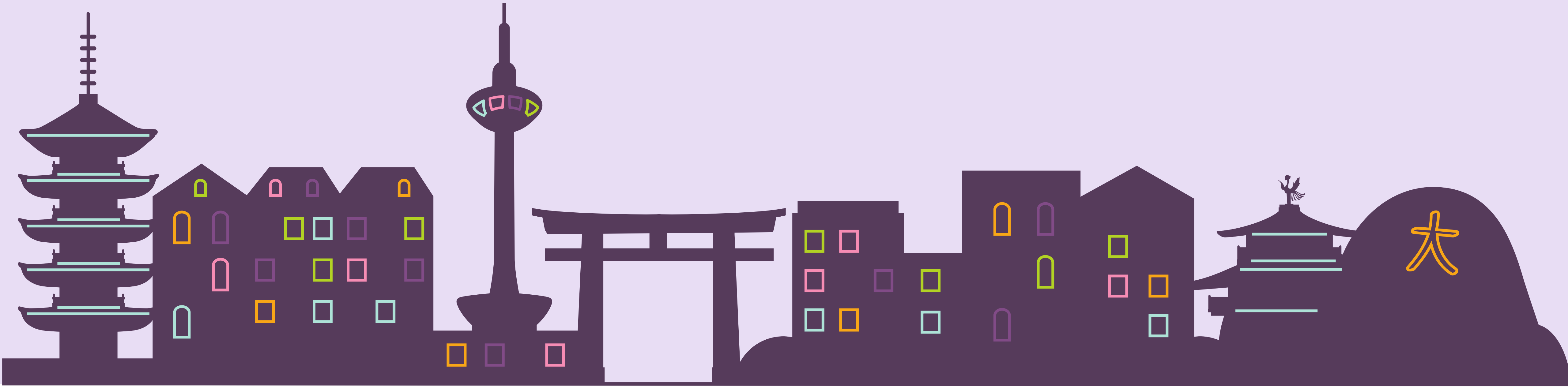
The higher the assistance the greater the EMG reductions in almost all muscles (flexors and extensors) in all tasks (static and dynamic)

1. Expected result for static tasks
2. In dynamic tasks, in both EXO conditions, the net gravitational torque at the shoulders was always sufficient to perform extension movements without causing overexertion of the antagonist muscles
3. In no cases, did the assistance cause detrimental effects on the antagonist muscles

Limitations and future works

- While the results of electromyographic activity should be considered as the first proof of the efficacy of the proposed algorithm, the exploratory nature of the tests did not permit to investigate some important factors that could influence EMG results (e.g., duration of the trials and experience of the subjects).
- The algorithm is highly dependent on features' values and does not consider for external load conditions (e.g., tools weight).

- **Future works** will focus on refining the algorithm (e.g., tailoring to user's anthropometry) and testing with a wider pool of subjects in more realistic environments, namely in real work tasks and in longer trials, where also the effects of fatigue might be assessed.



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