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ScuDo
Scuola di Dottorato ~ Doctoral School
WHAT YOU ARE, TAKES YOU FAR

Concept of an exoskeleton for industrial applications with modulated impedance based on electromyographic signal recorded from the operator

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XXX cycle audictions, Ph.D. in Mechanical engineering, 2nd year

Introduction

- Humans
  - naturally developed algorithms for control of movement
  - forces a human could exert are limited by muscle strength
  - muscle strength may decrease with aging, fatigue, or neuromuscular diseases
- Robotic manipulators
  - high forces
  - lower flexibility and quality of performance

Coupling a robotic device with an human operator might represent an interesting solution

- Main exoskeleton characteristics:
  - wearable device
  - direct man-machine interaction
    - robot → human
    - human → robot

Robot → Human

- Intrinsic characteristics of the exoskeleton
  - → cognitive (exoskeleton gives feedback to the operator)
  - → biomechanical (exoskeleton applies controlled forces on the operator)

Exoskeleton generations

Human $\xrightarrow{\text{Controls}}$ Robot

First generation: used to assist human locomotion and to apply a set of predefined joint angle trajectories.

Second generation: two control strategies are commonly applied.

- an open-loop control is involved such that a pre-specified force or torque value is applied based on the position.
- a control proportional to the force/torque exchanged between the user and the exoskeleton.

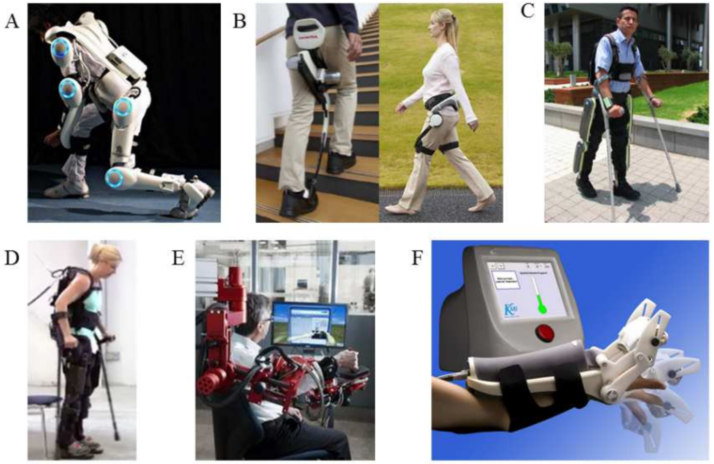
Third generation: the exoskeleton was driven using an EMG signal.

Fourth generation: the device get the signal directly from the brain with non-invasive electroencephalogram (EEG) or with invasive action measuring directly from the motor cortex

Exoskeleton fields of applications

Military

Rehabilitation



Industry

Exoskeleton and arm stiffness

During manufacturing works, operators interact with unstable environment.

Operators need to stiffen their limbs

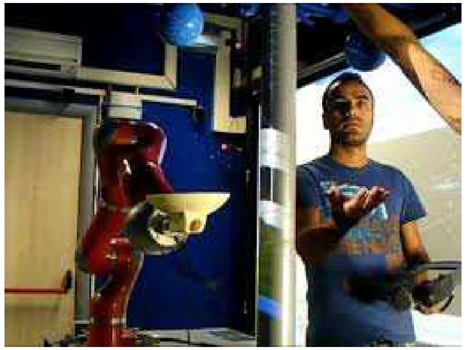
Achieved co-activating muscles

Fatigue

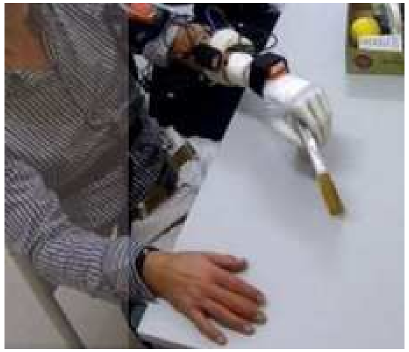
Muscular diseases

Robotic devices whose impedance is modulated with Electromyographic signal

Robotic systems



Prosthesis



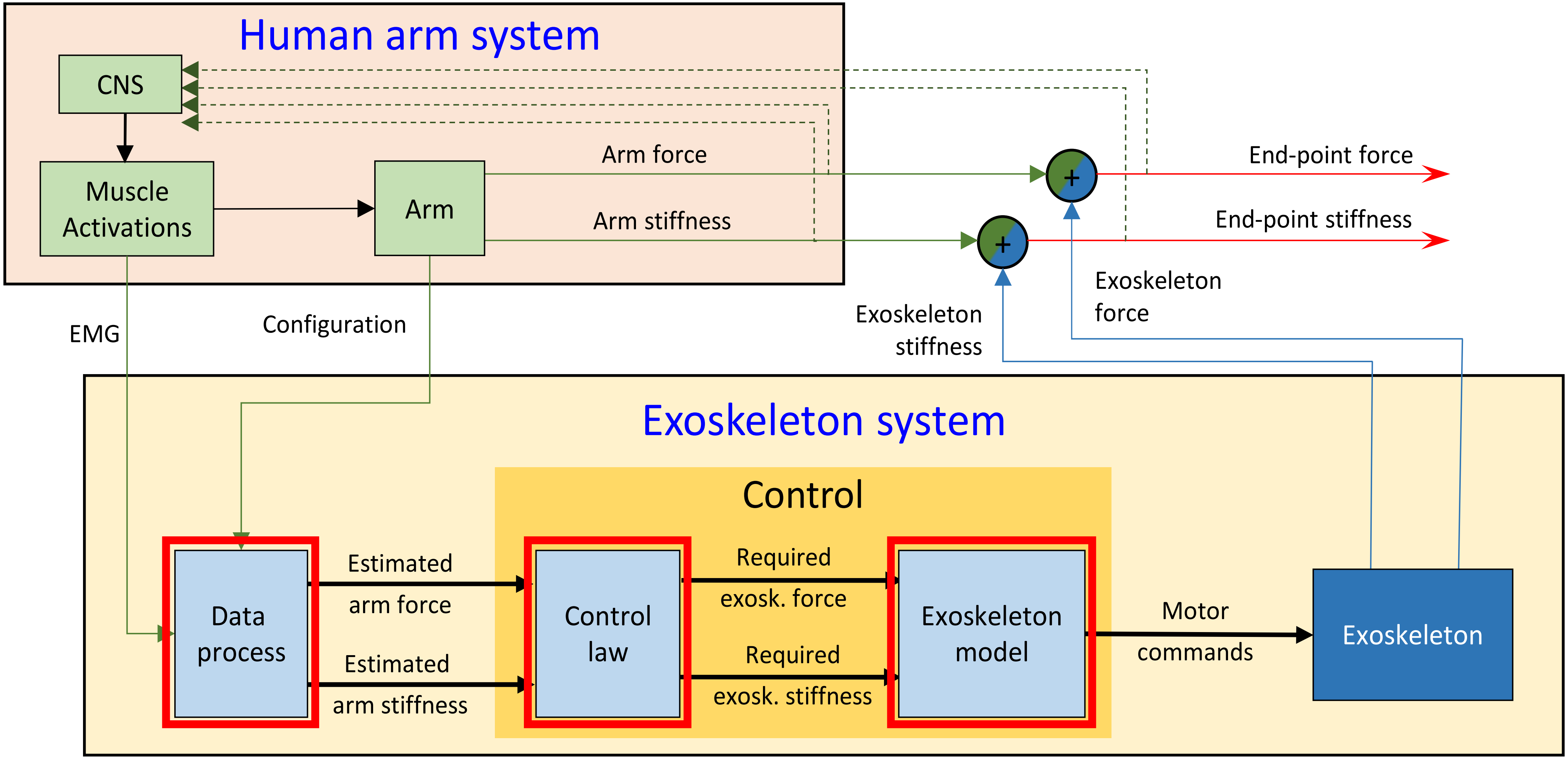
Exoskeletons

Introduction: Task definition

Kinematic characteristics of the task

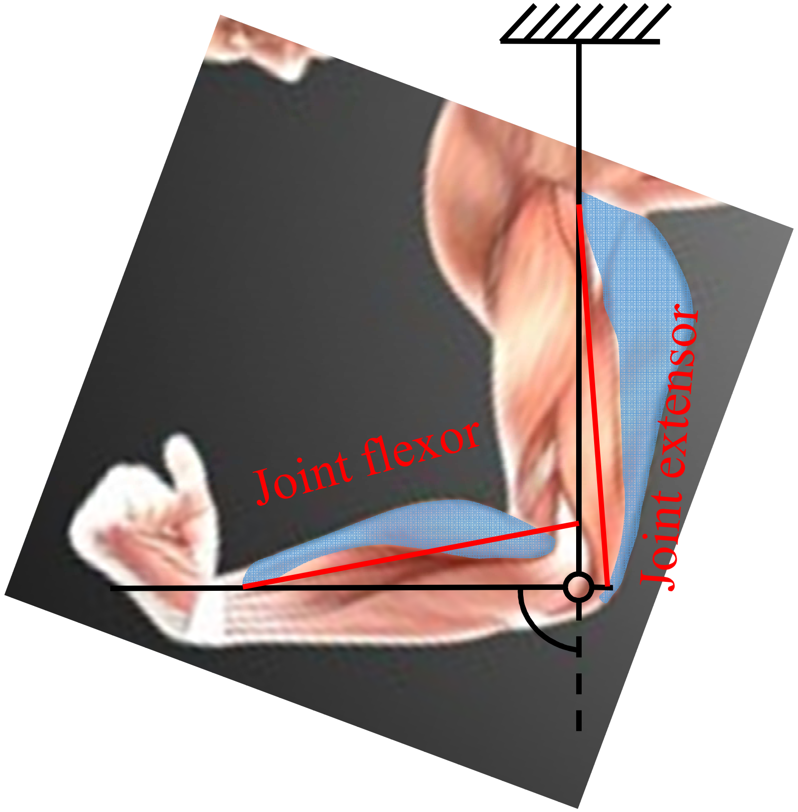
		Isometric operations	Dynamic operations
Kind of instability	Continuous instability	Isometric operations Continuous instability 	Dynamic operations Continuous instability 
	Spiky instability	Isometric operations Spiky instability 	Dynamic operations Spiky instability 

Concept of human-exoskeleton interaction

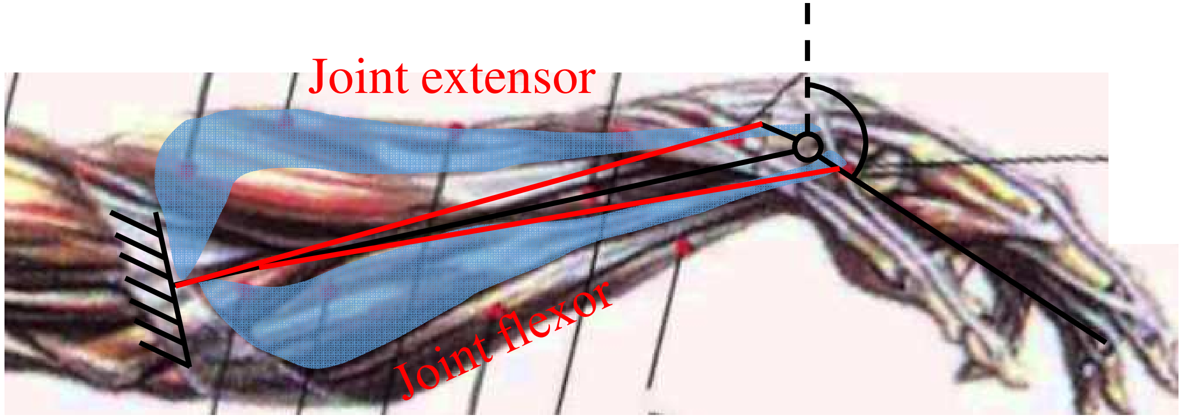


The model of 1 joint and 2 muscles

Elbow



Wrist

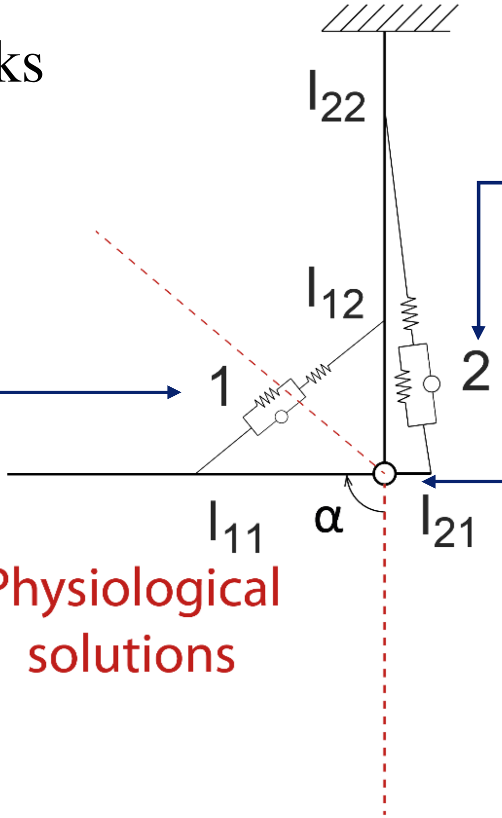


The model of 1 joint and 2 muscles

One joint and two links

Actuator 1: Flexor;
Brachioradialis
(BRD)

Opposed directions of
the muscles actions



Actuator 2: Extensor;
Lateral head of the Triceps
(TriLat)

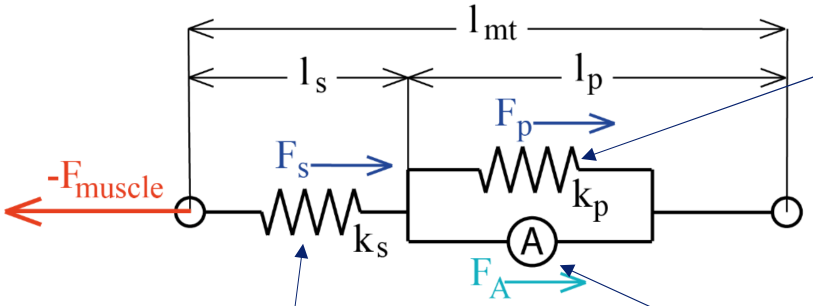
Hinge joint

Physiological
solutions

Muscles are
approximated with wires

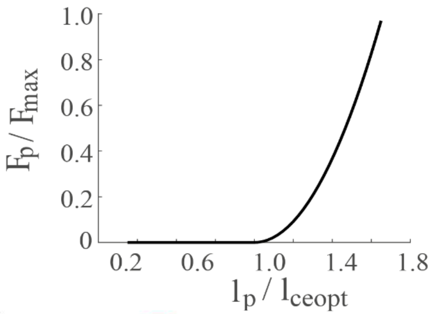
Muscles model

The musculo-tendon systems are approximated on the basis of the model developed by Hill[1].



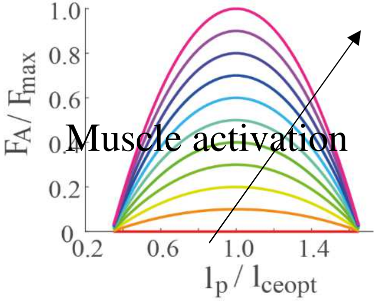
non-linear spring in parallel
with A (collagen tissue)

$$F_p = k_p \left[\max\left(0, \frac{l_p}{l_{ceopt}} - \frac{l_{p0}}{l_{ceopt}}\right)\right]^2$$



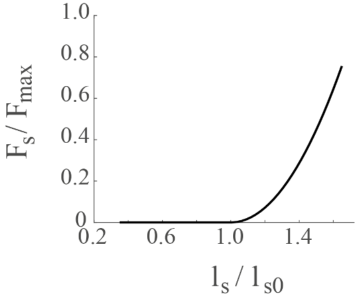
active element A (actin-myosin action)

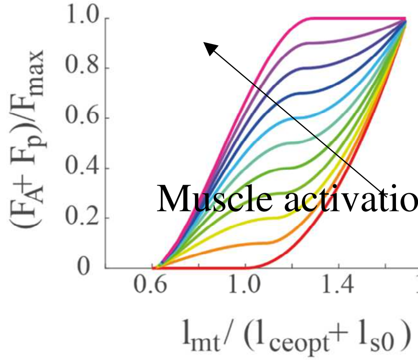
$$F_A = m \cdot F_{MAX} \cdot \left[-a \cdot \left(\frac{l_p}{l_{ceopt}}\right)^2 + 2a \cdot \frac{l_p}{l_{ceopt}} - a + 1\right]$$



non-linear spring in series
with A (tendon segment)

$$F_s = k_s [\max(0, l_s - l_{s0})]^2$$



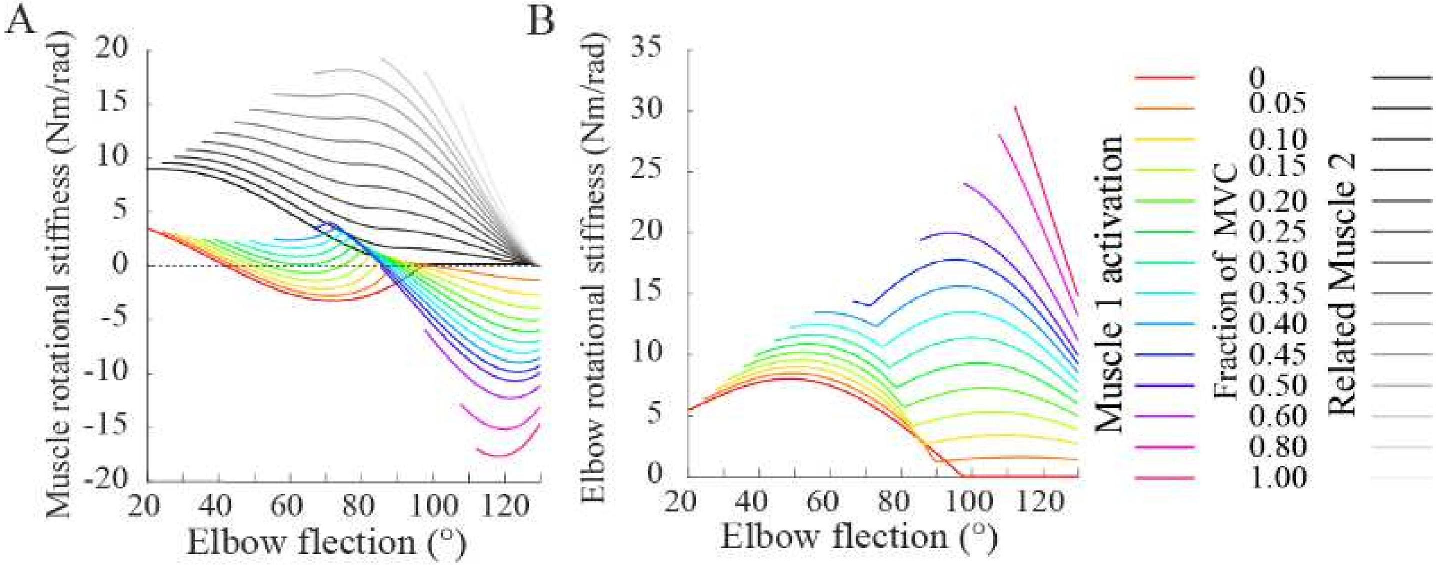


[1] A. V. Hill, 1953

Muscle and joint stiffness

Muscle *i* stiffness $$K_i = -\frac{\partial\left(m_{a_i}\cdot\left(F_{pi}+F_{Ai}\right)\right)}{\partial\alpha} = -\left(m_{a_i}\frac{\partial\left(F_{pi}+F_{Ai}\right)}{\partial\alpha} + \left(F_{pi}+F_{Ai}\right)\frac{\partial m_{a_i}}{\partial\alpha}\right)$$

Small deflection of 0.01° is applied to the elbow joint (positive and negative) → A corresponding torque at the elbow is calculated



Rotational stiffness of the elbow: difference between the slopes of the elbow angle-torque curves of muscle 2 respect with muscle 1

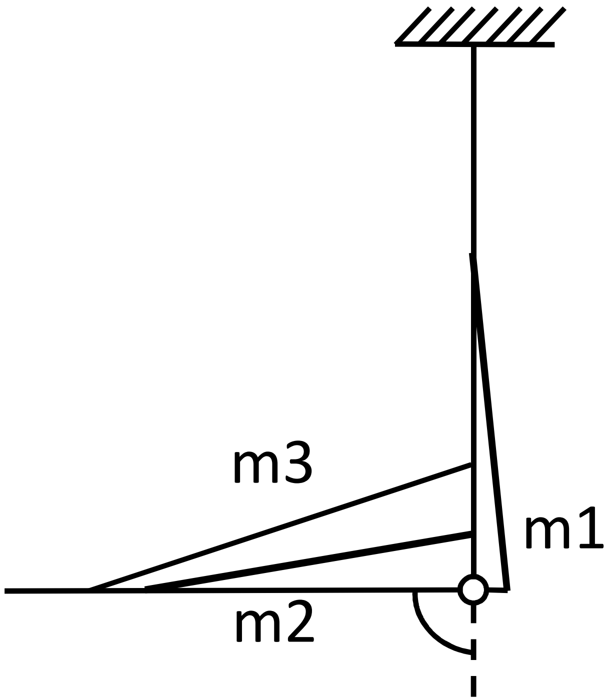
Borzelli, D.; Pastorelli, S.; Gastaldi, L.; *Model of the human arm stiffness exerted by two antagonist muscles*. In: RAAD, 2016, Belgrade

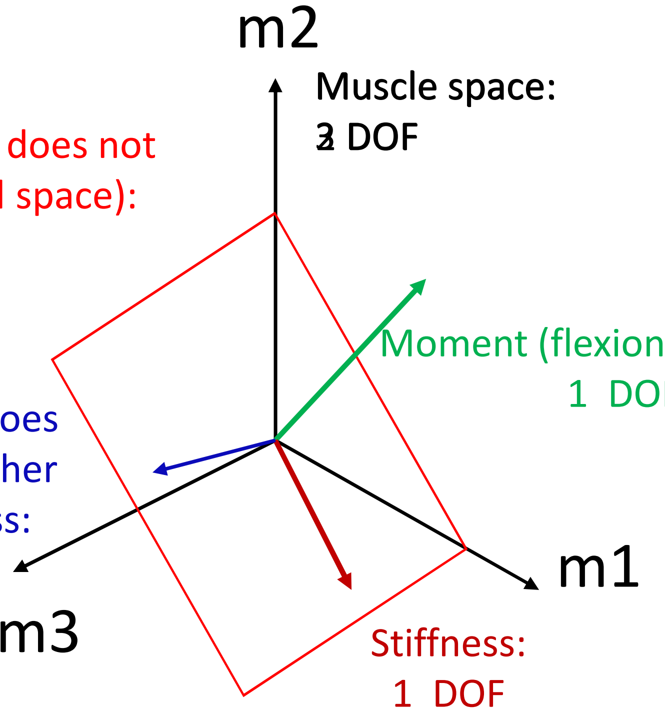
Borzelli, D.; Pastorelli, S.; Gastaldi, L.; *Determination of the human arm stiffness efficiency with a two antagonist muscles model*; In: IFToMM Italy, 2017, Vicenza

Borzelli, D.; Pastorelli, S.; Gastaldi, L.; *Concept of an upper limb exoskeleton for industrial applications with modulated impedance based on operators arm stiffness,* Int. J. Automotive Tech., 2017

Estimation of the operator stiffness

Joint model with 3 muscles





Muscle space:
3 DOF

Muscle component that does not exert any moment (null space):
3-1 = 2 DOF

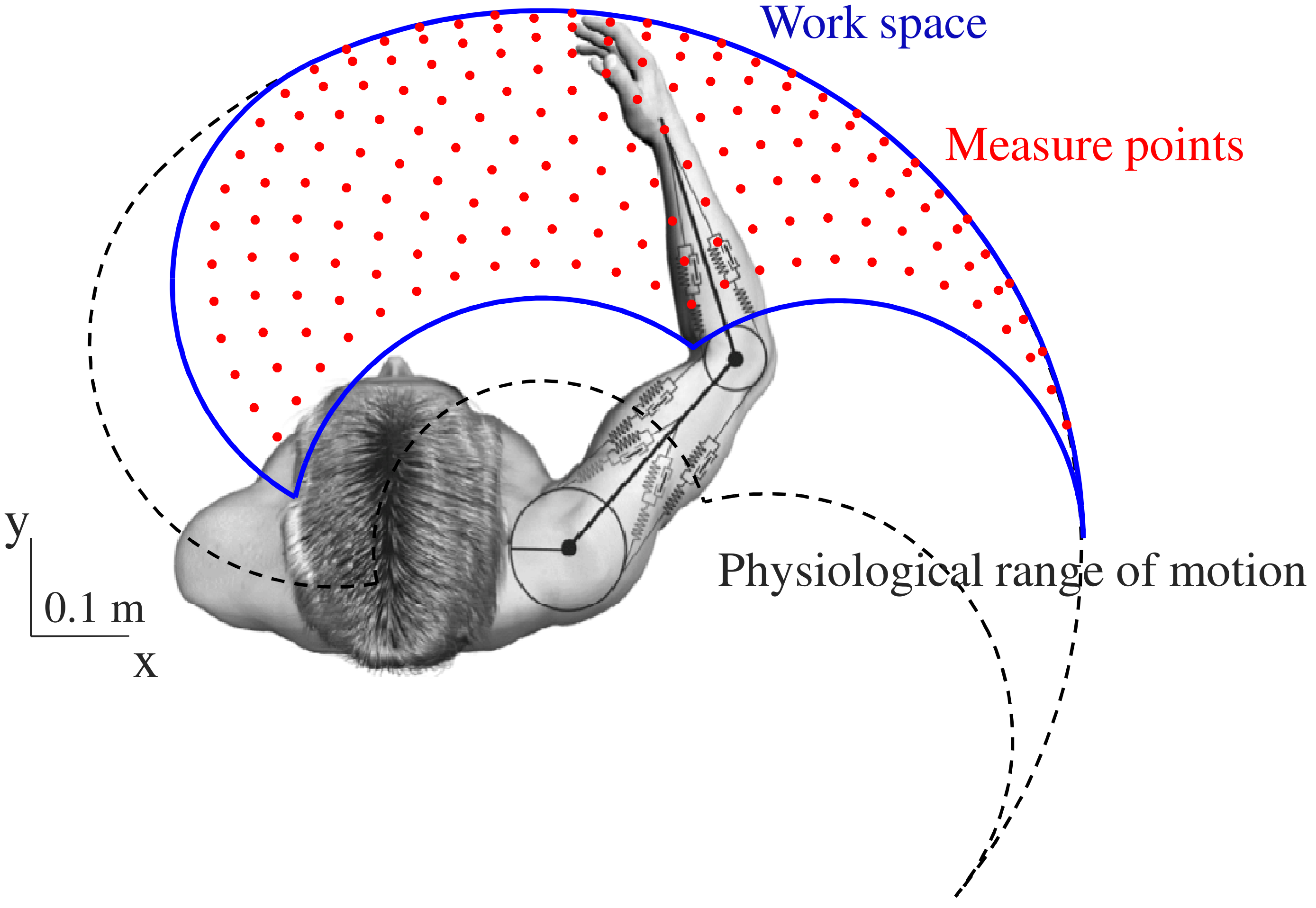
Moment (flexion-extension):
1 DOF

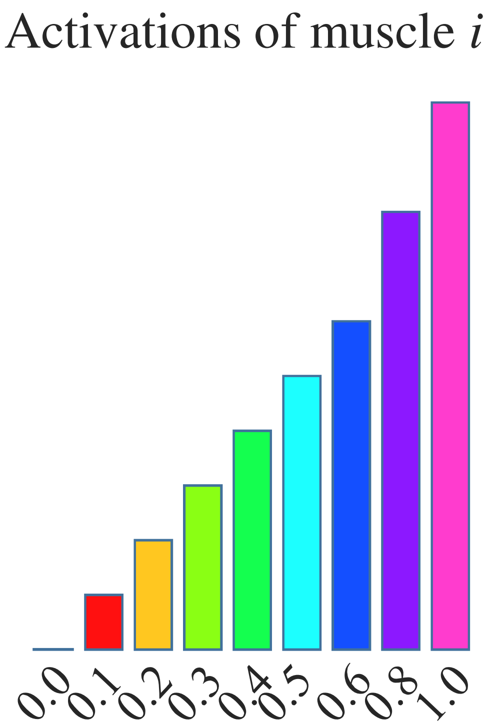
Component that does not generates neither force nor stiffness:
1 DOF

Stiffness:
1 DOF

Is the null space a reasonable approximation of the subject stiffness during isometric tasks?

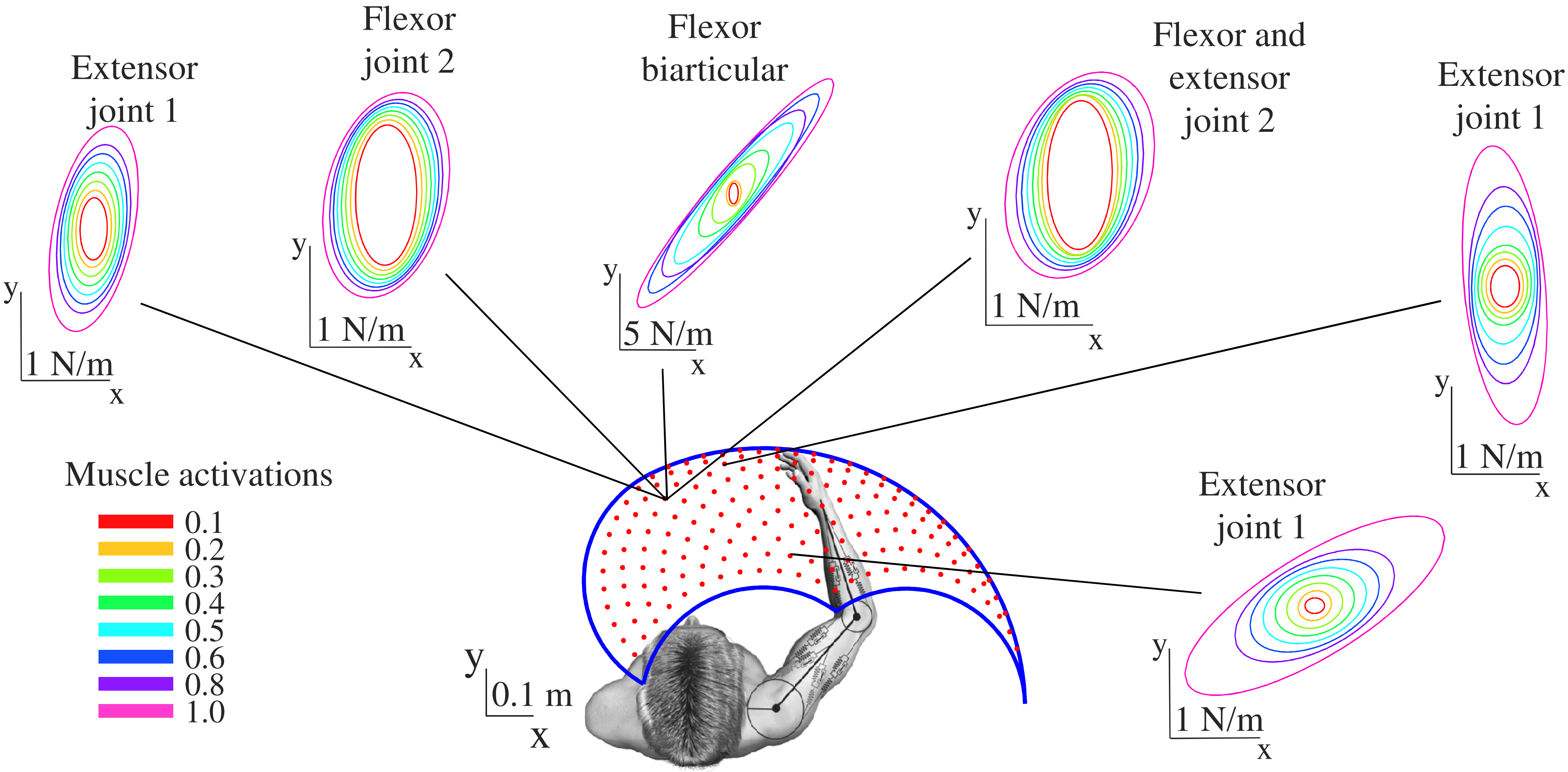
The model of 2 joints and 6 muscles





All combinations of muscle activations were tested

Stiffness ellipse



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The model of 2 joints and 6 muscles

The major axis a, the minor axis b, and the area of the stiffness ellipse were calculated for each end-point position and muscle pattern.

The projection of the muscle activation onto the null-space was calculated: $n = N^T N \cdot m$.

A regression r between of the stiffness, calculated for each muscles patterns in which all the activations of each muscle were lower or equal to i, where i = 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.8, 1.0, and n was calculated.

The Variance Accounted For (VAF):

$$VAF = 1 - \frac{\sum (y_i - r \cdot n)^2}{\sum {y_i}^2}$$

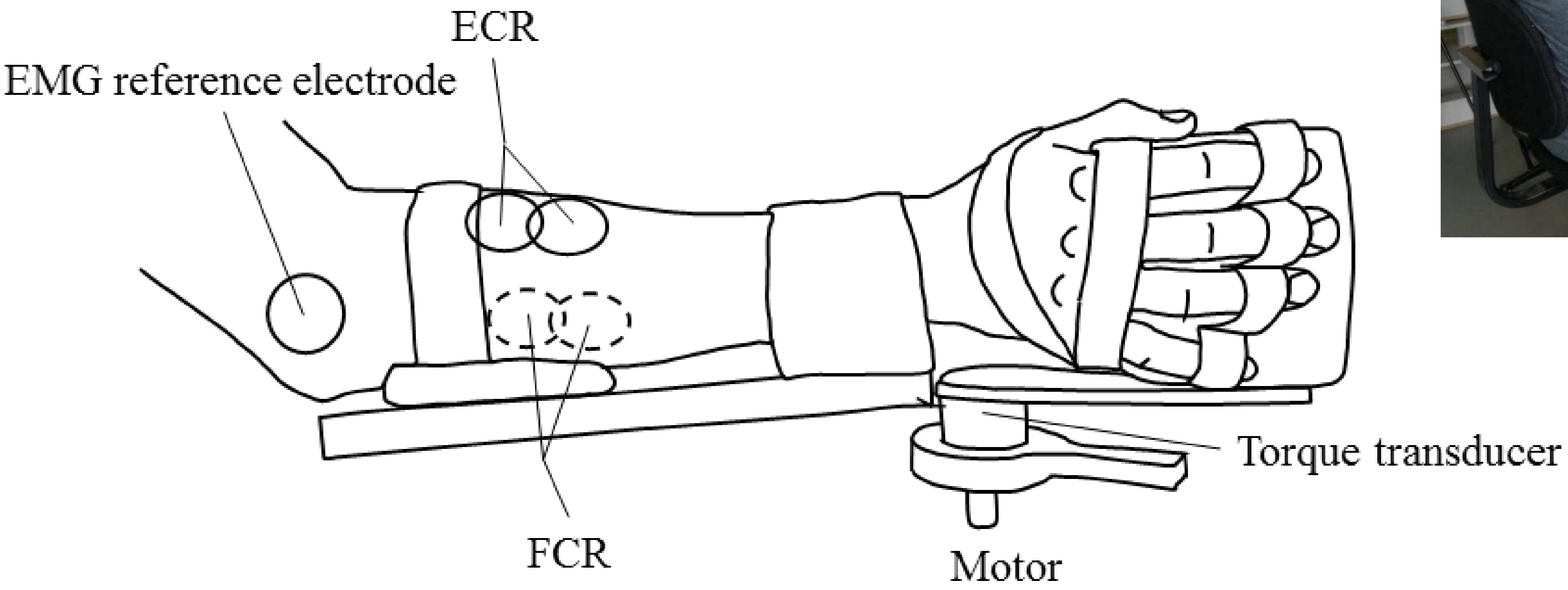
Where y_i could be a, b, or the area of the ellipse

VAF	≤ 0.1	≤ 0.2	≤ 0.3	≤ 0.4	≤ 0.5	≤ 0.6	≤ 0.8	≤ 1.0
a	0.762	0.518	0.403	0.314	0.256	0.218	0.193	0.170
b	0.652	0.468	0.377	0.324	0.272	0.230	0.186	0.152
area	0.548	0.306	0.196	0.128	0.090	0.069	0.051	0.038

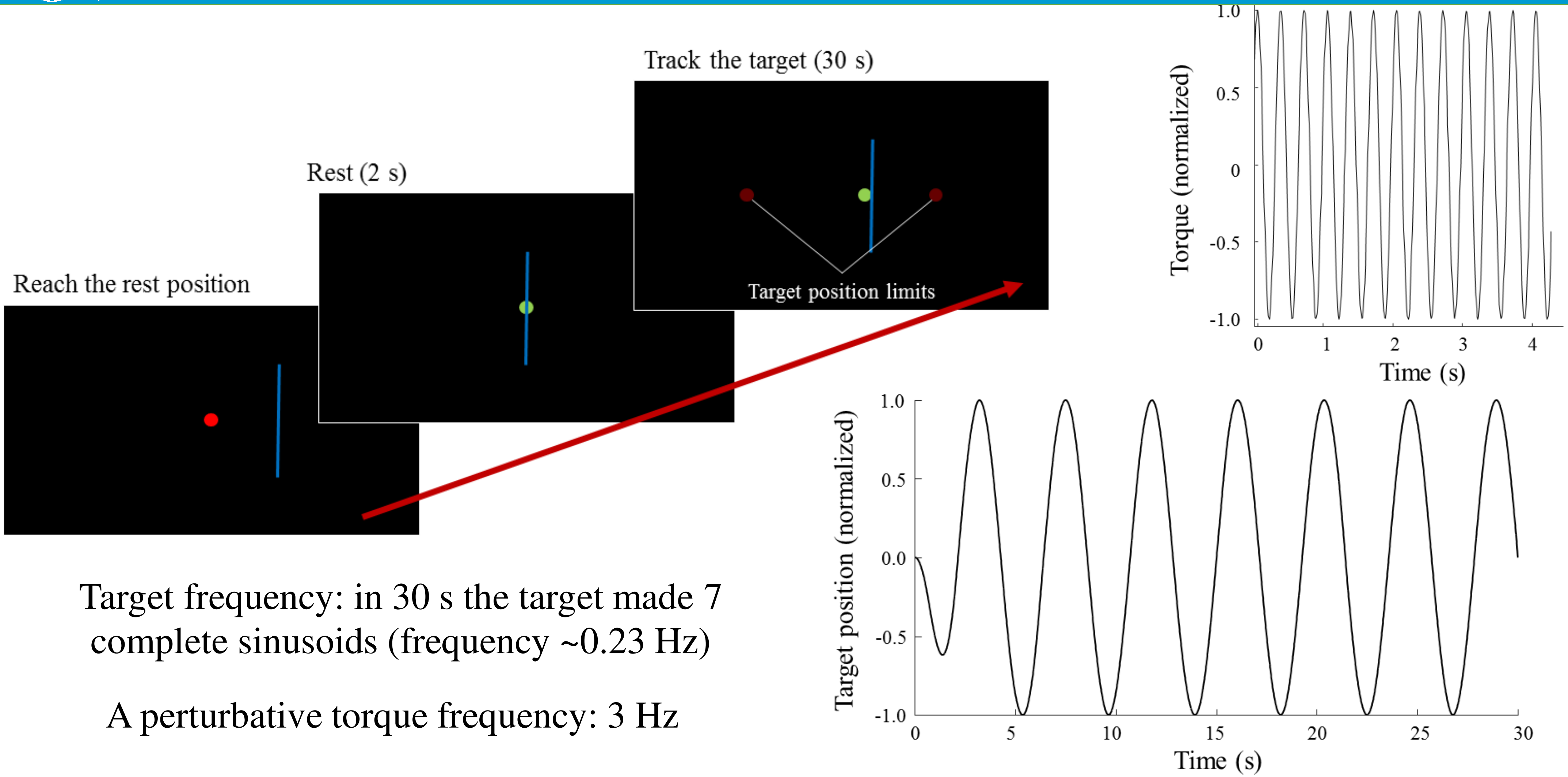
A linear regression between the null space and the stiffness ellipse major axis was identified if the regression was conducted on muscle patterns whose activations were all lower than a value between 0.2 and 0.3

Setup

Hi5



Task



Target frequency: in 30 s the target made 7 complete sinusoids (frequency ~0.23 Hz)

A perturbative torque frequency: 3 Hz

Command logics

Baseline

No reduction of the perturbation

Proportional

perturbation reduced, sample by sample, proportionally to the co-contraction

Integral on 1s

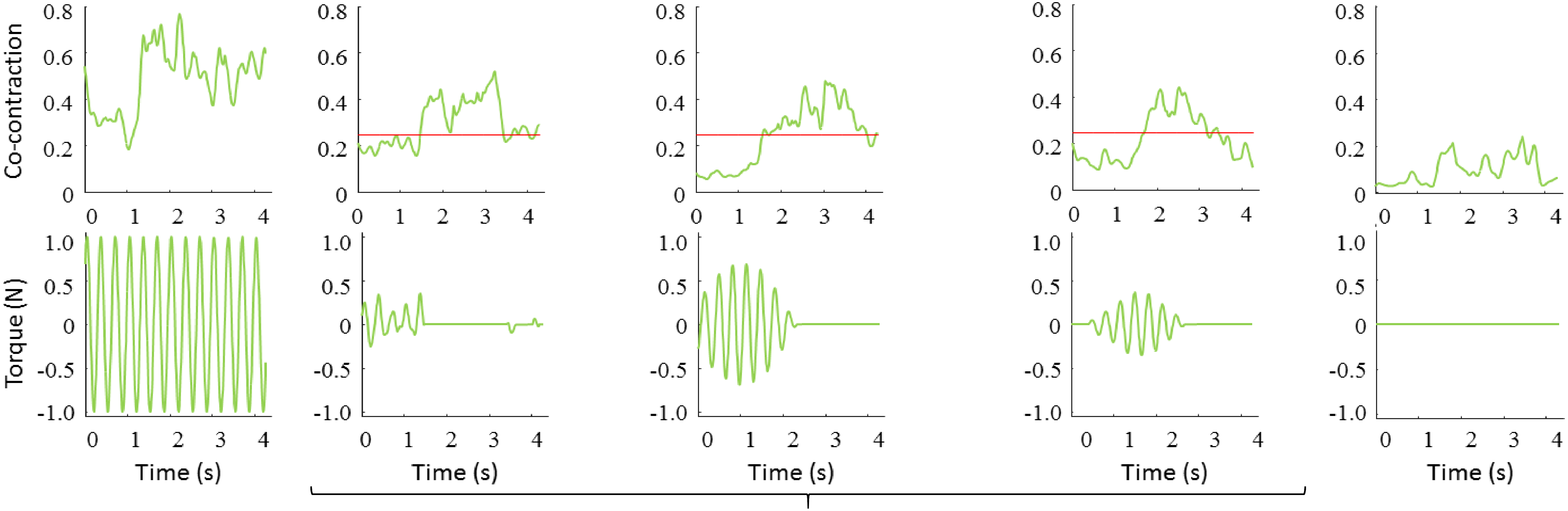
perturbation reduced proportionally to the mean co-contraction recorded in the previous 1 s

Integral on 2s

perturbation reduced proportionally to the mean co-contraction recorded in the previous 2 s

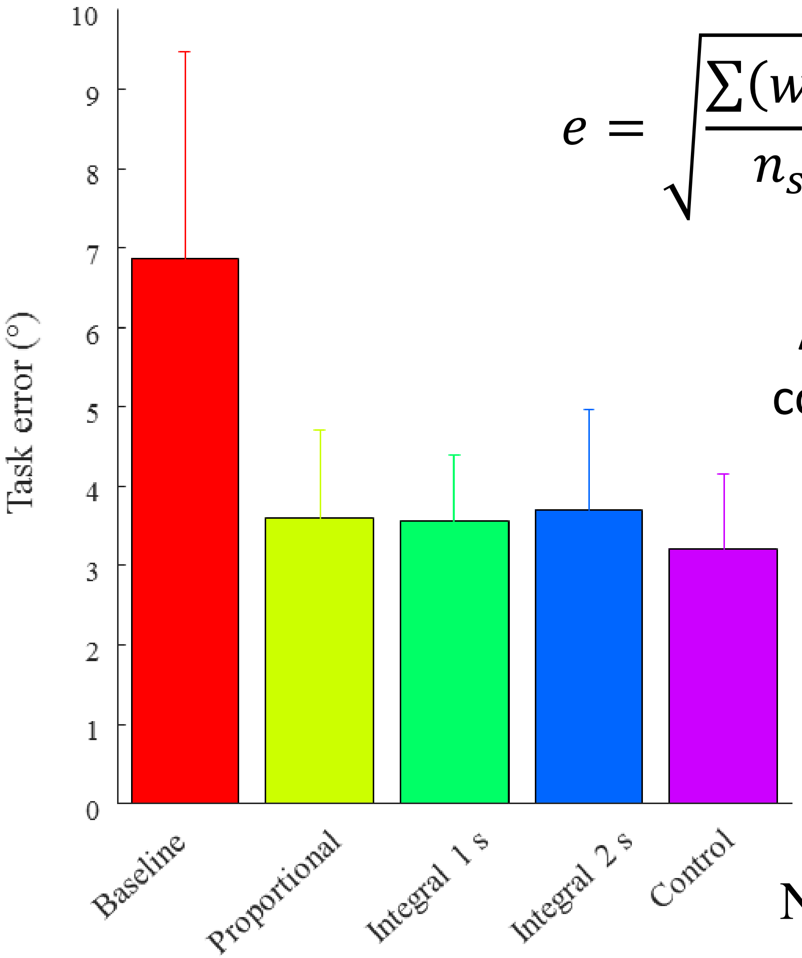
Control

No perturbation



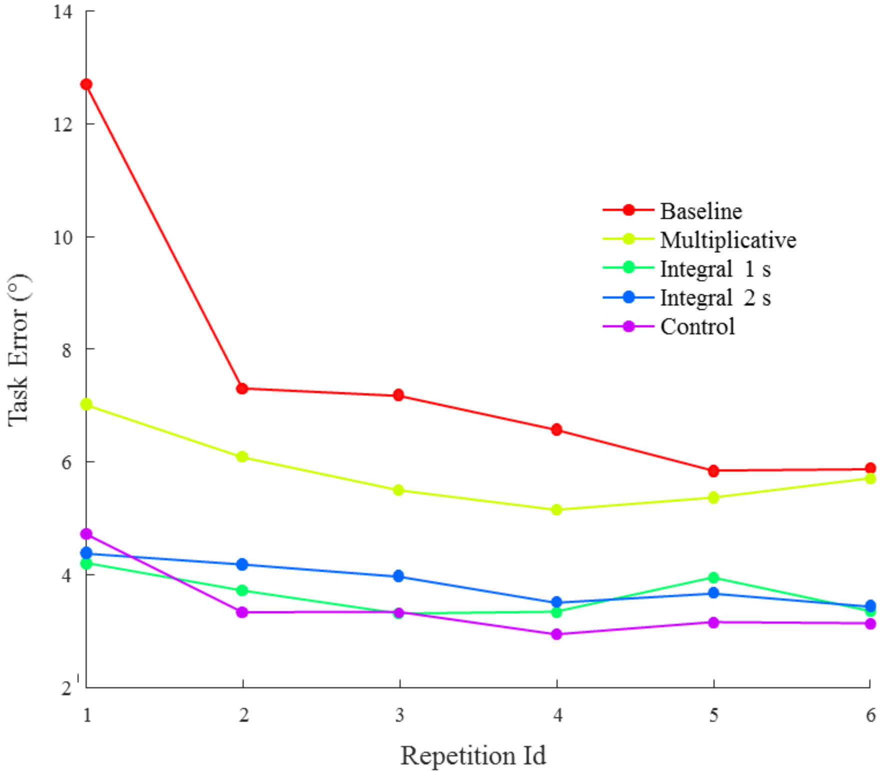
Randomly shuffled

Task error



$$e = \sqrt{\frac{\sum (w_a - t_a)^2}{n_{samples}}}$$

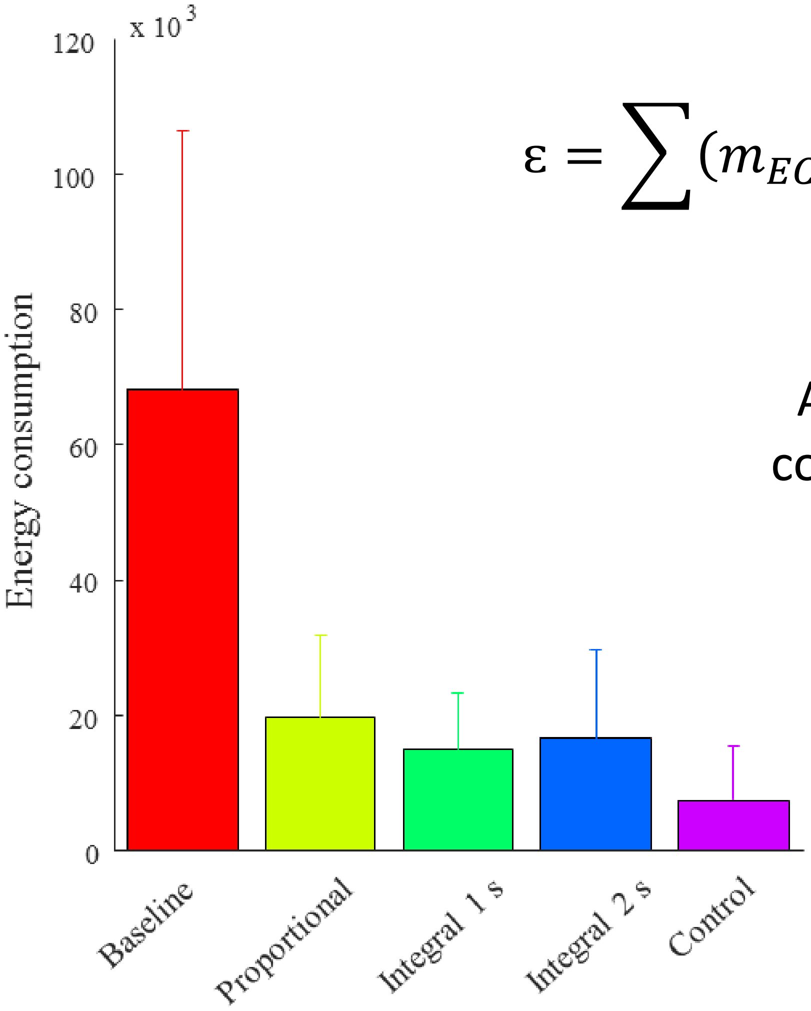
ANOVA on each couple of sessions



A statistical difference the Baseline and the Control and the all other sessions.

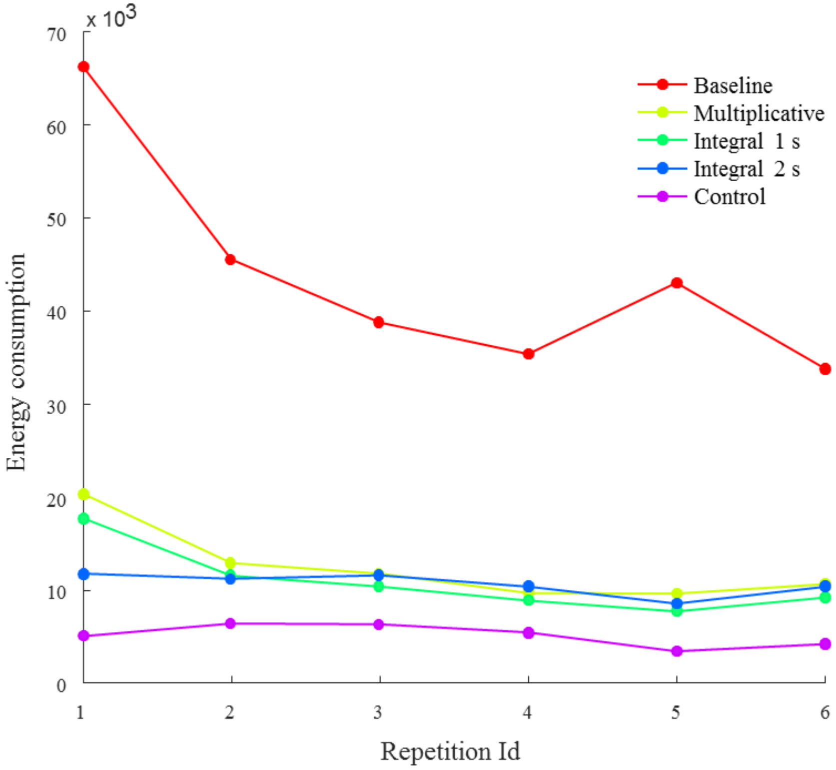
No statistical difference between the sessions in which an external aid was given to the subject

Energy consumption



$$\varepsilon = \sum (m_{ECR} + m_{FCR})^2$$

ANOVA on each couple of sessions



A statistical difference the Baseline, the Control, and the Proportional and the all other sessions.

No statistical difference between the Integral sessions

Command logic

An aid from an external device led to beneficial effects both in terms of task error and energy consumption

The same task error was obtained during Proportional and Integrals logics

The Integrals command logics should be preferred to the Proportional based on the energy consumption

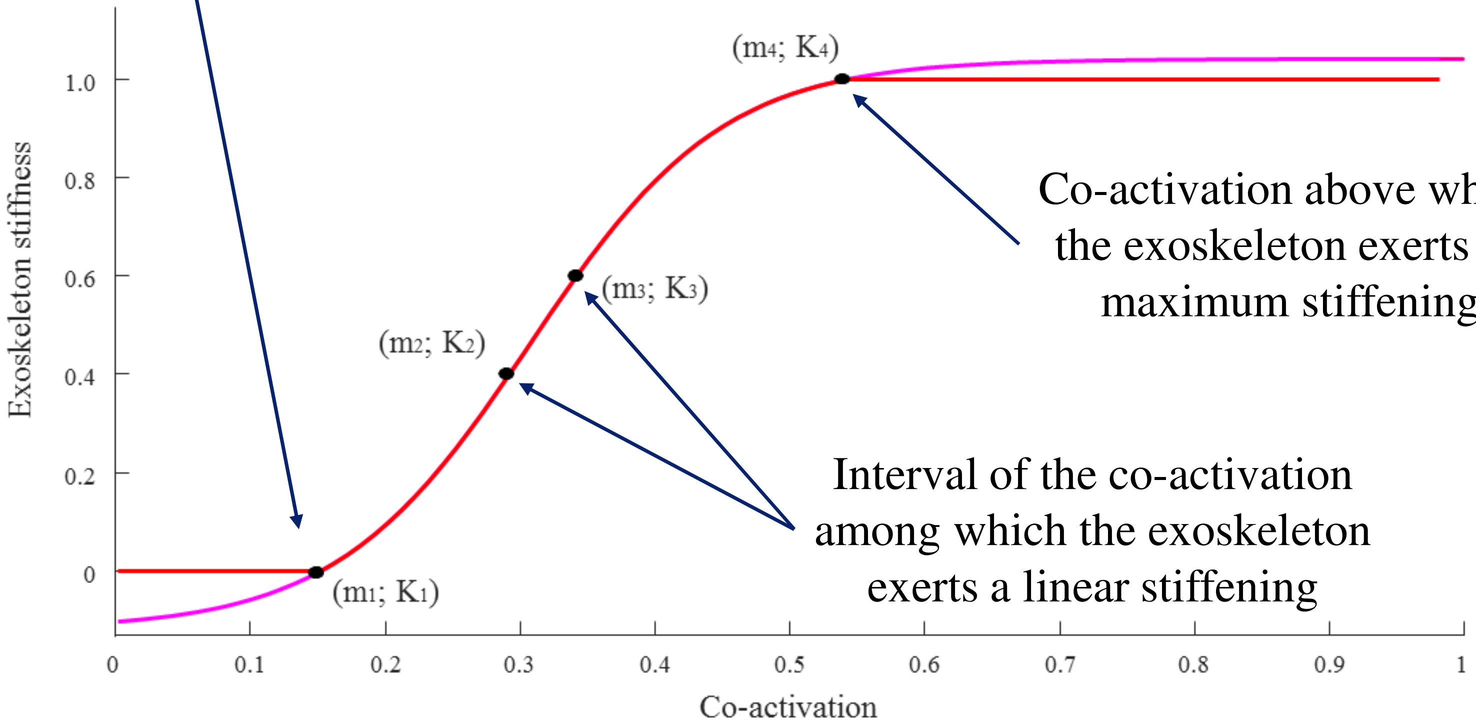
Integral logics are better for controlling an external device that modulates the stiffness based on the operator muscle co-contraction

No influence of the integration time

Command logic parameters

A logistic curve relates the muscle co-contraction *m* and the stiffness exerted by the exoskeleton *K*

$$K = a\frac{b \cdot e^{-m/\tau} + 1}{c \cdot e^{-m/\tau} + 1}$$



Co-activation below which no stiffening was exerted by the exoskeleton

Co-activation above which the exoskeleton exerts its maximum stiffening

Interval of the co-activation among which the exoskeleton exerts a linear stiffening

Actuator

The logics implemented in the selected Variable Stiffness Actuator (VSA) were compared and the VSA was selected such that

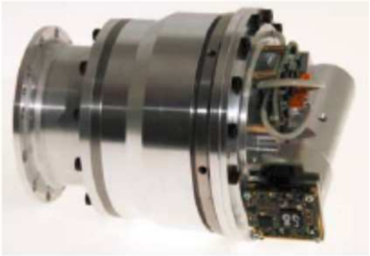
The VSA modulates the stiffness even if no perturbation does occur (no software control)

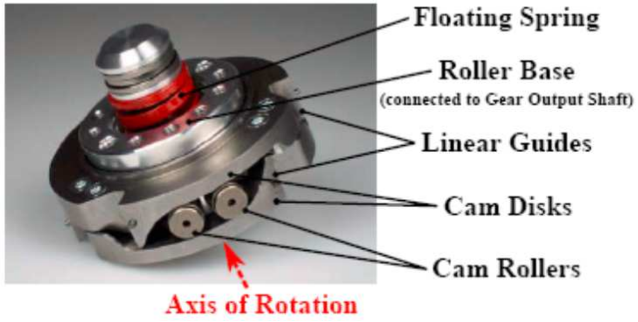
The VSA stiffness should change during the task

Implemented in an existing exoskeleton that enhance the operator’s force:

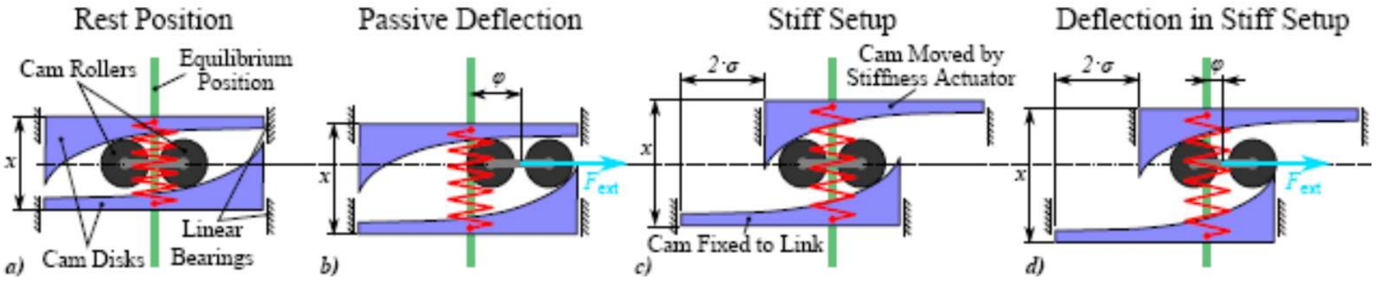
the VSA should be compact

the VSA should only exert stiffness and not force (exerted by the existing actuators)





The DLR FSJ was selected



Conclusions

The command logic of an exoskeleton, whose impedance was modulated based on the operator stiffness, calculated from EMG signal, was proposed.

The stiffness of the operator was estimated based on the projection of the muscle activation into the end-point null space.

An integral logic was experimentally identify to be the best logic to estimate the effort the exoskeleton should exert on the operator.

A logistic law, whose parameters were experimentally calculated, relates the subject null space with the amplitude of the stiffness the exoskeleton needs to exert.

The actuator that could modulate the stiffness was identified as the DLR FSJ


THANK
YOU
GRACIAS
ARIGATO
SHUKURIA
MERCI
BOLZİN
BİYAN
SHUKRIA
MEHRBANI
GRAZIE
SUKSAMA
TASHAKKUR ATU
YAQHANYELAY
DANKSCHEEN
JUSPAXAR
KOMAPSUMNIDA
GOZAIMASHITA
EFCHARISTO
EKHMET
PALDIES
MAAKE
TINGKI
MINMONCHAR
MAKETAI
SIKOMO
EKOJU
HATUR
GUI
UNALCHEESH
YUSPAGARATAM
HUI
SPASIBO
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