Development of an artificial muscle for a soft robotic hand prosthesis

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Energétique Mécanique Electromagnétisme

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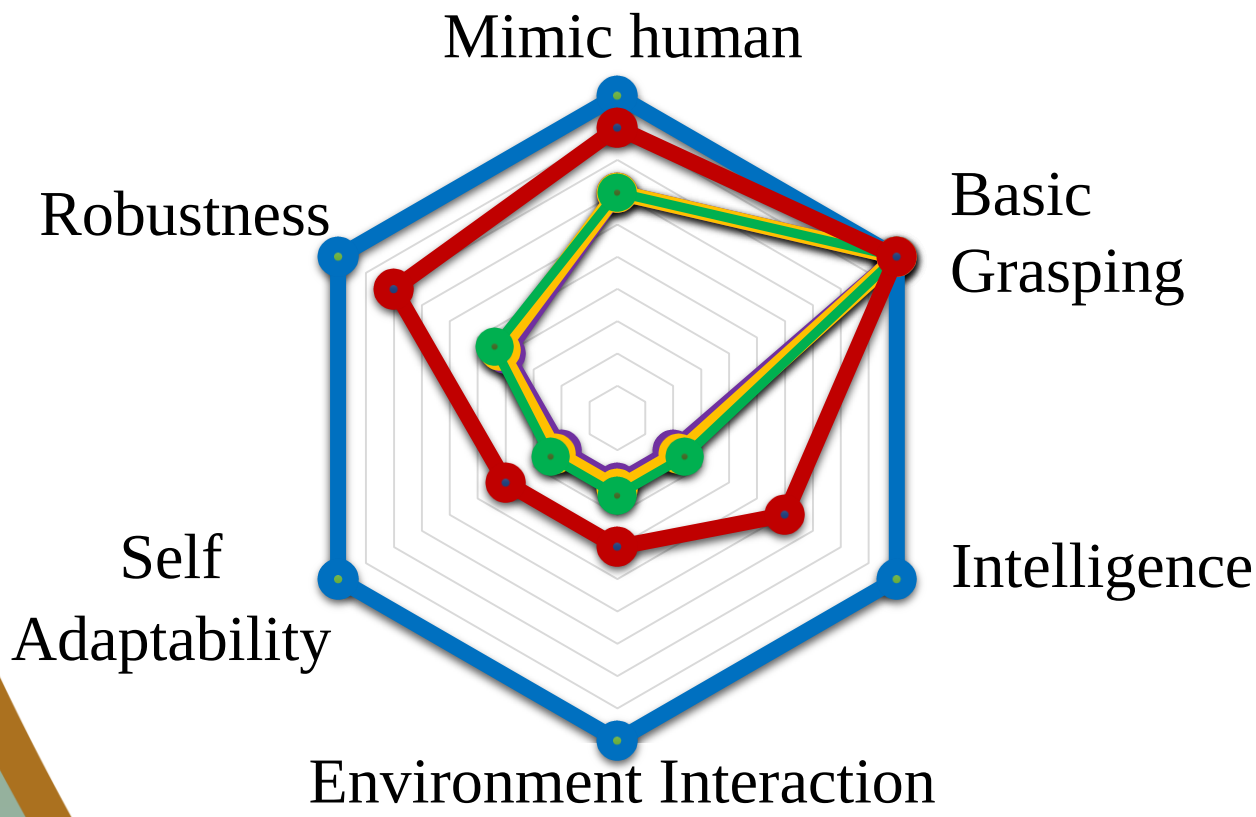
Context

2009 – 2013
10 253 amputees
(Vicepresidencia, 2013)

Advances in robotic hand prosthesis




Human


i-limb


Bebionic

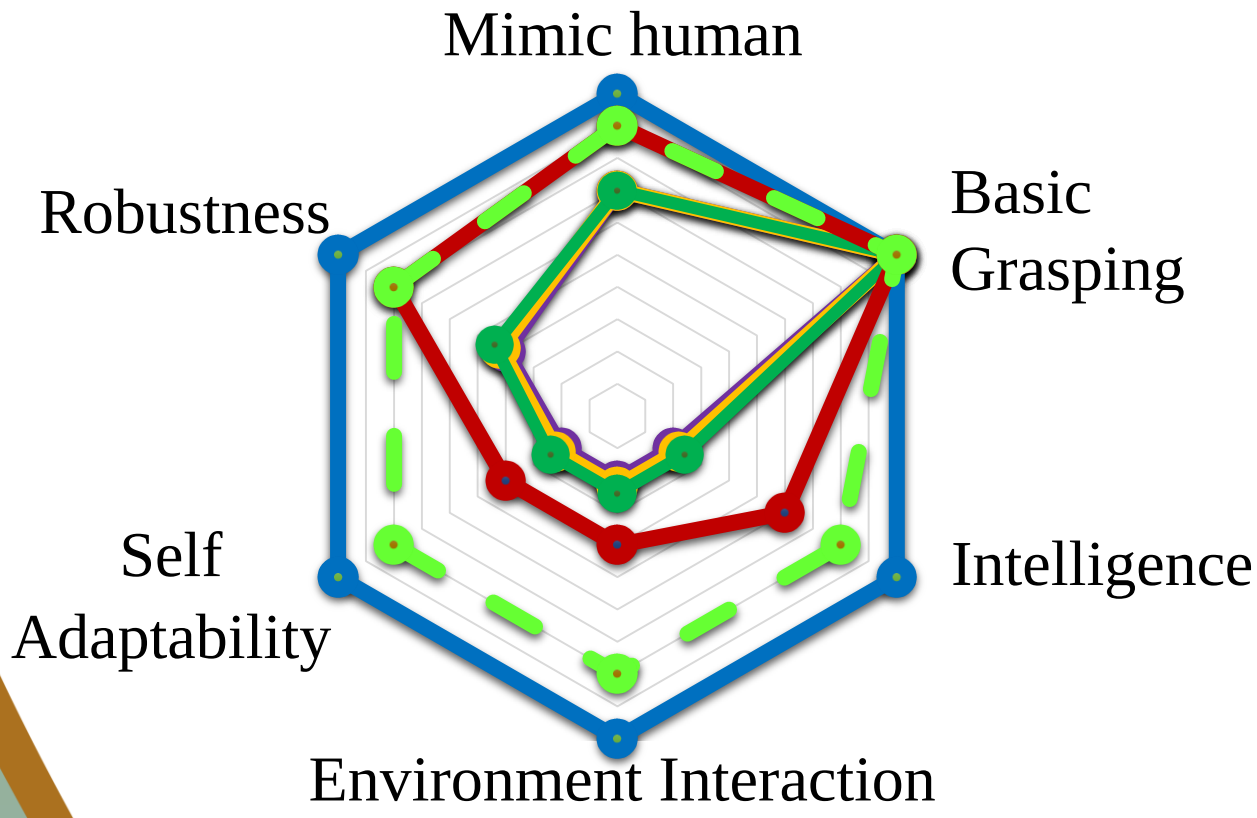

Michelangelo


Robioss

Commercial Prostheses

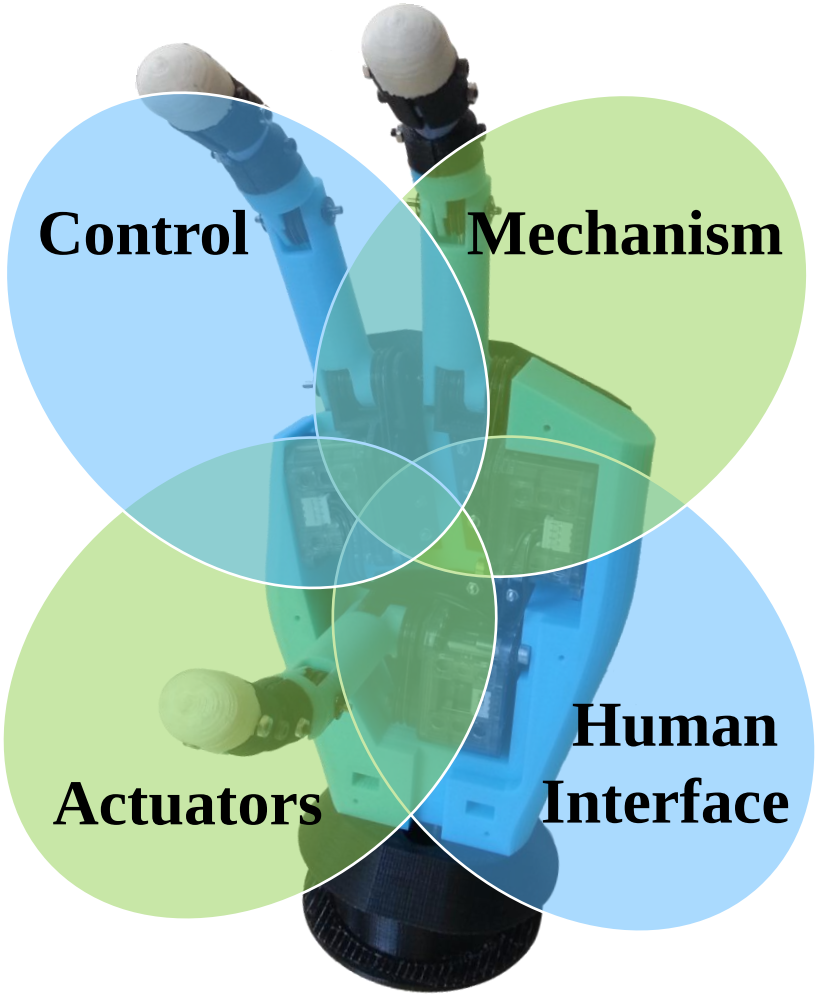
Research Purposes

Enhance hand prostheses capabilities



- Emulating **human hand adaptability and flexibility**
- Development better adapted **mechanism**
- Using unconventional and **smart materials**
- **Improving actuators** for hand prostheses requirements

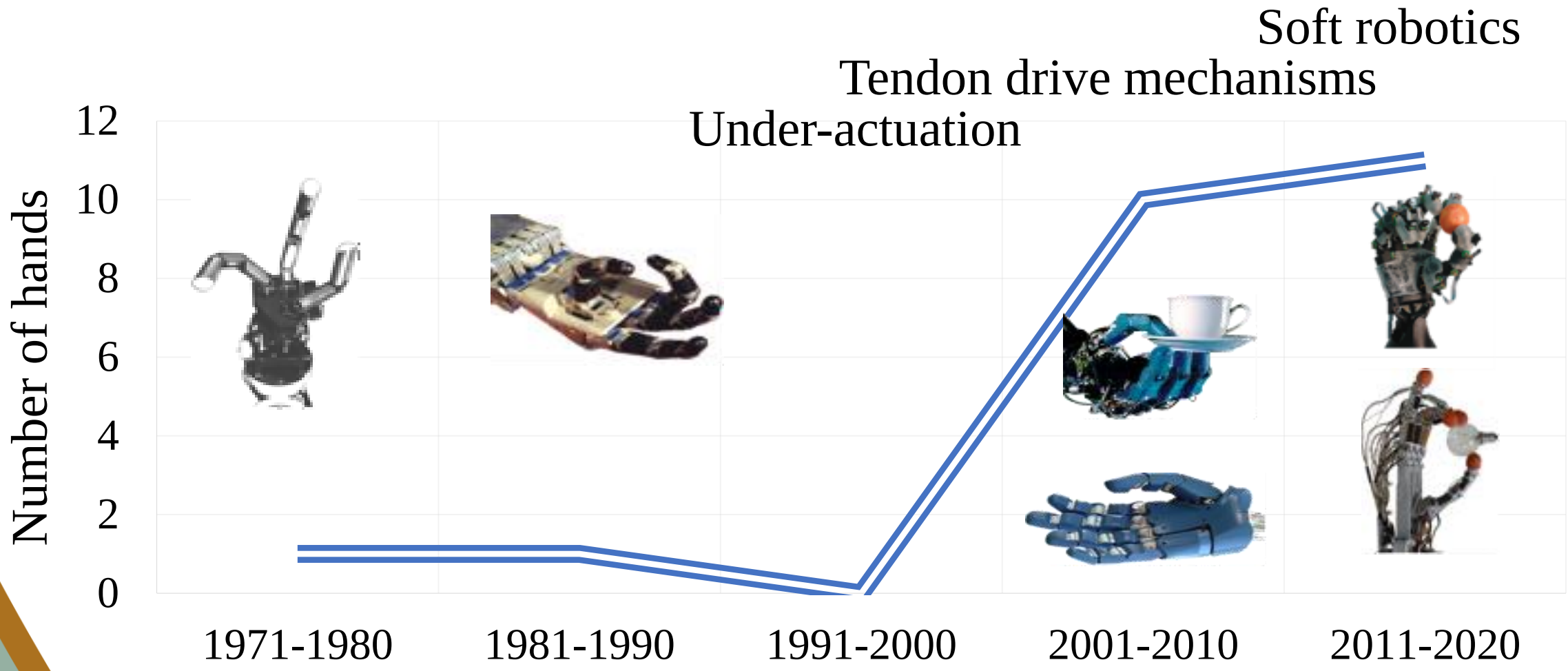
Research axes



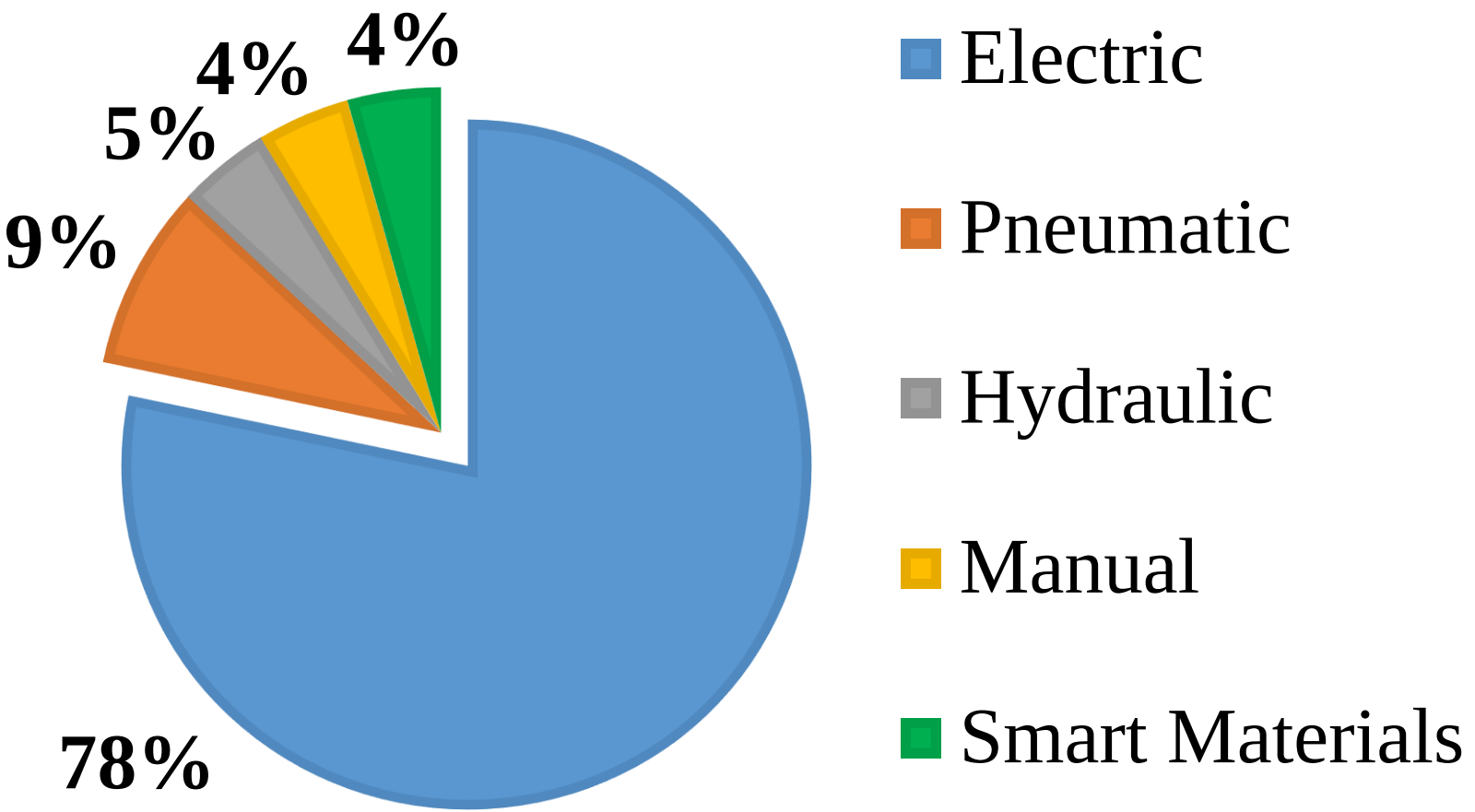
Outline

1. Introduction
2. Analysis of the human hand
3. The ProMain-I Prosthesis
4. SMA based artificial muscle
5. Conclusions and perspectives

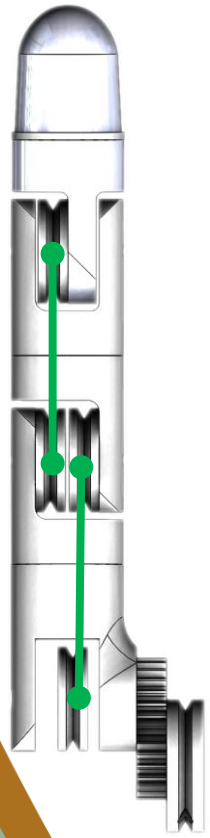
Introduction

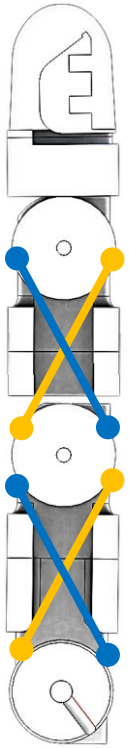


Research about actuation strategies

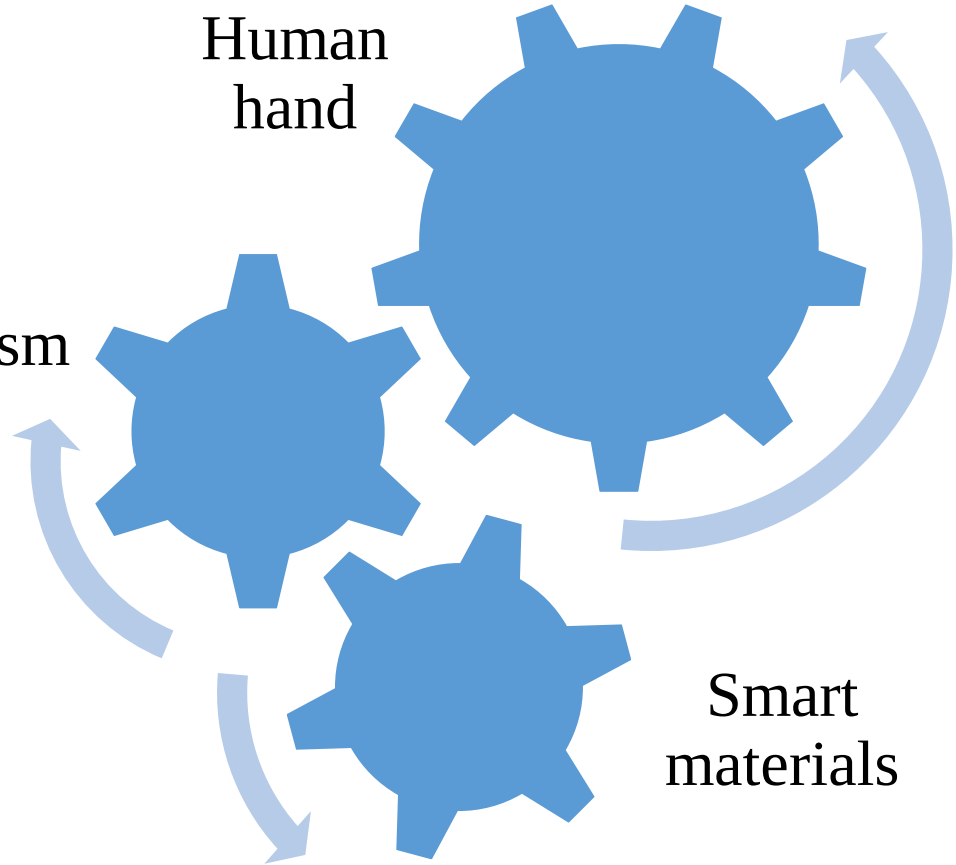


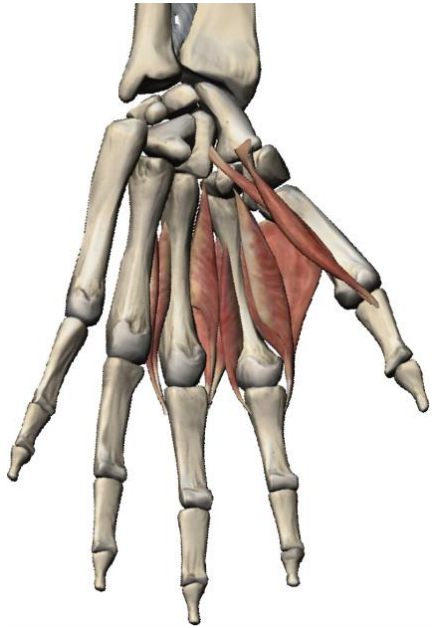
Approach to develop a new artificial muscle

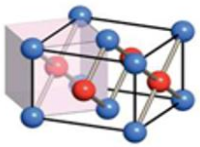




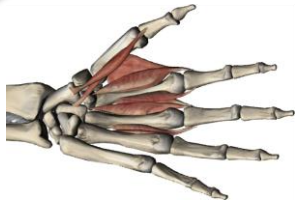
Robot Mechanism







Approach workflow



Biomechanical requirements

- Biomechanics
- Grasping
- Force assessment

Actuation Requirements

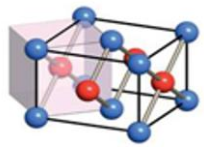
- Biomechanics
  +
- Robotics

- Design
- Modeling
- Assessment

Robotic mechanism

- Smart material selection
- Actuator design
- New prosthesis

Artificial muscle



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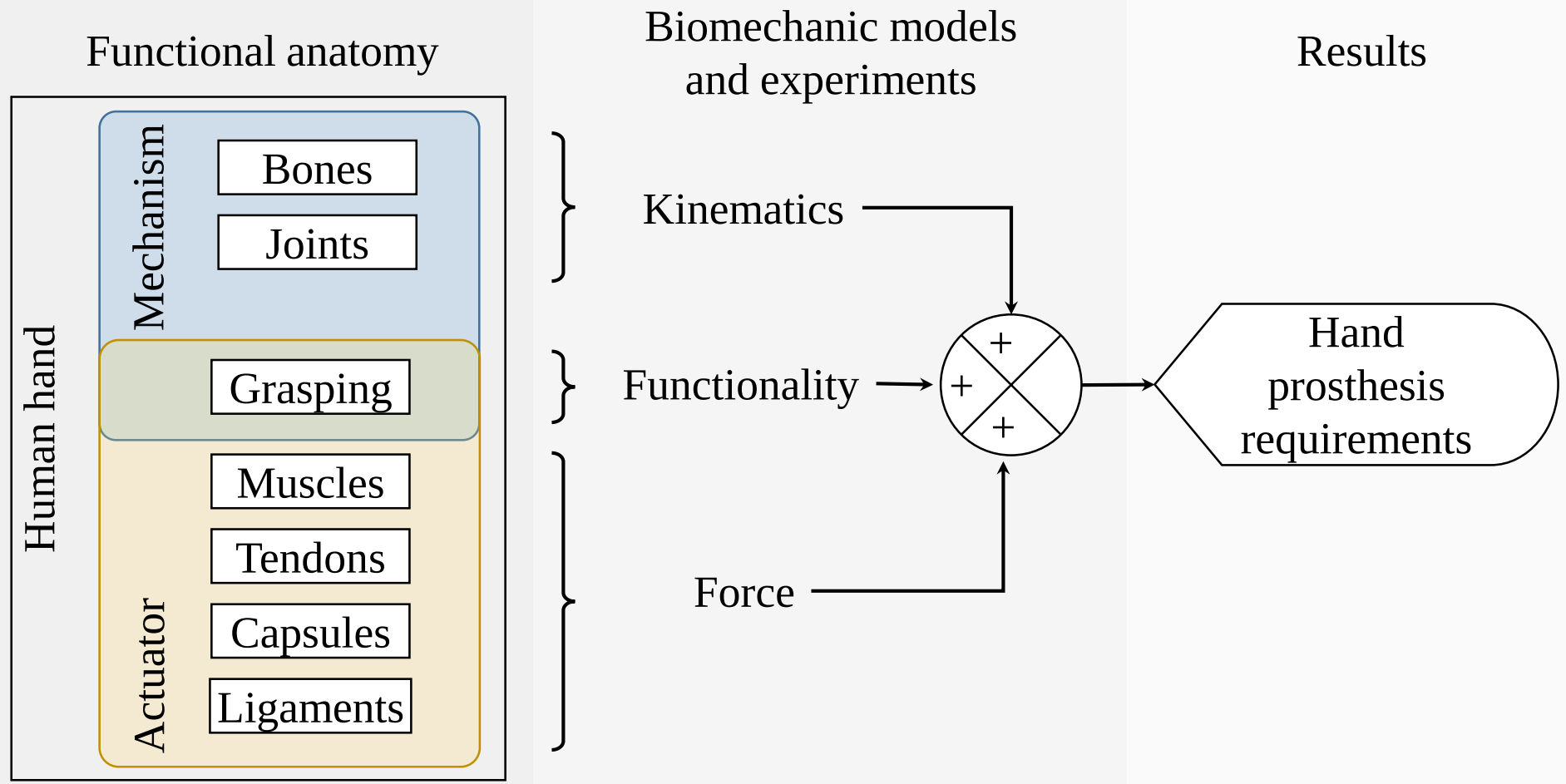
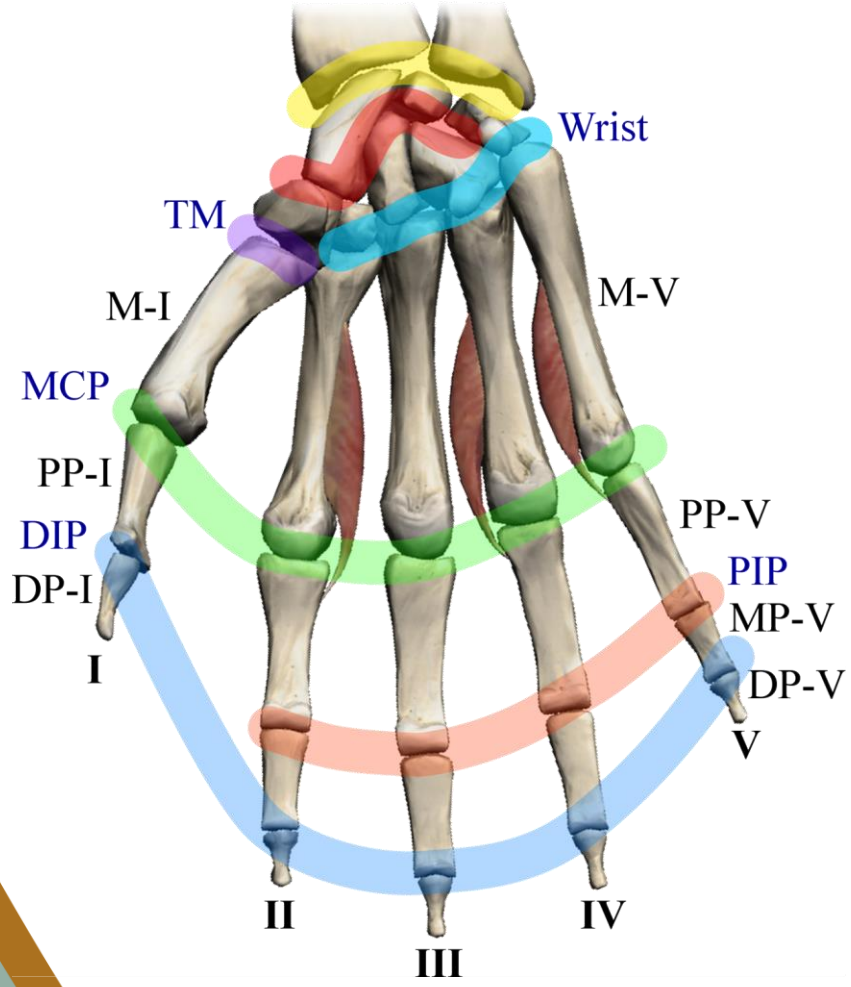
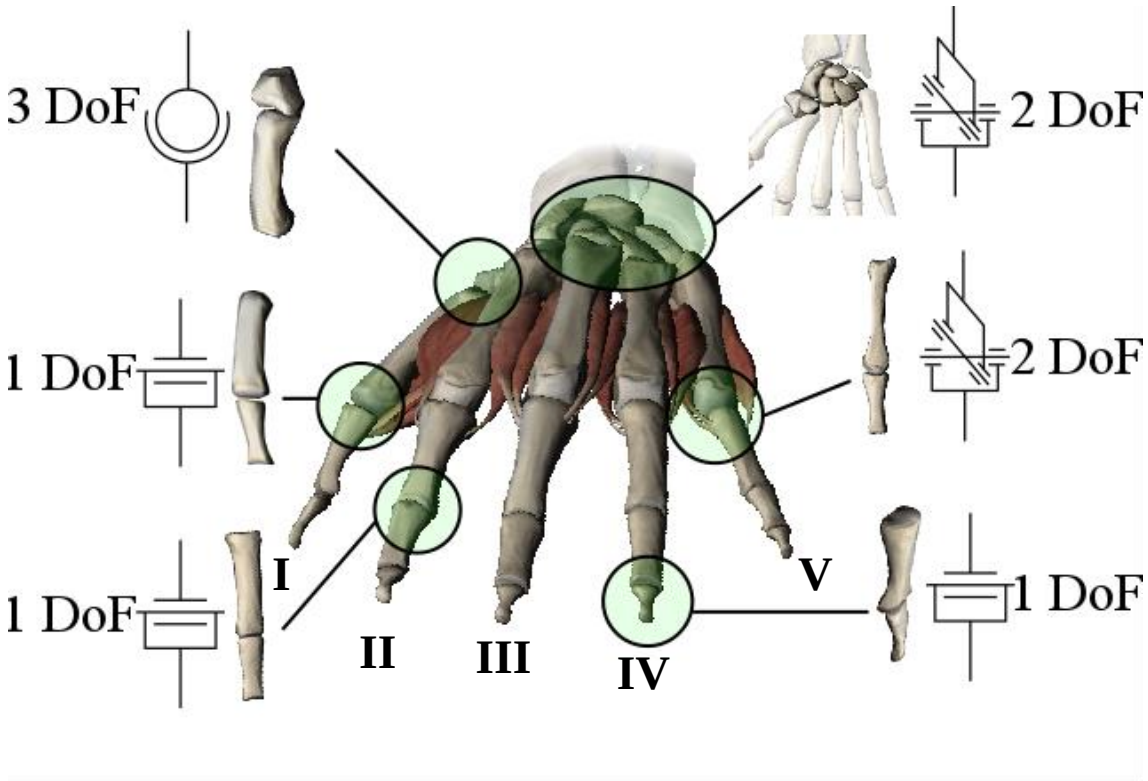
Evaluation of the human hand

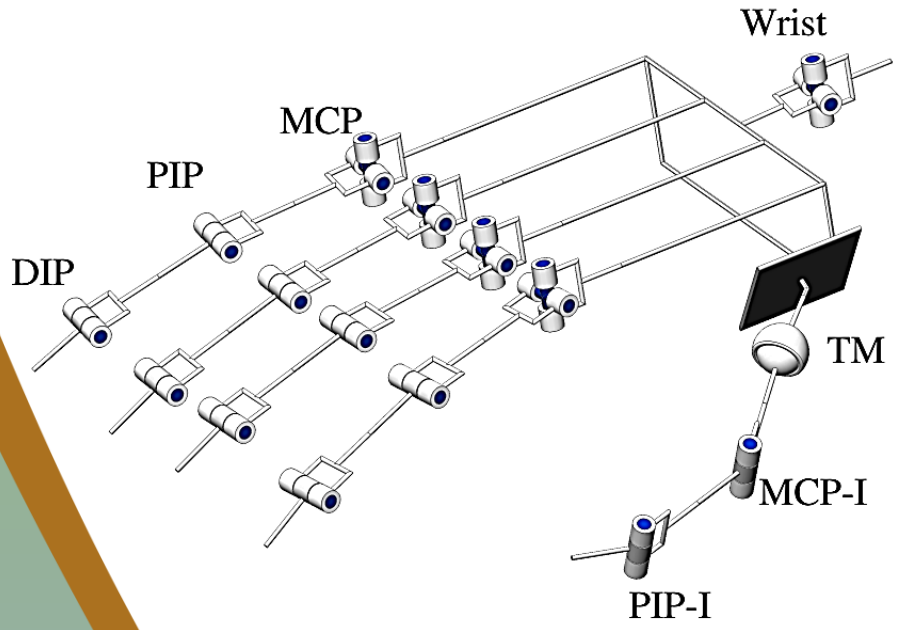


Bones and joints of the human hand





Equivalent mechanical model

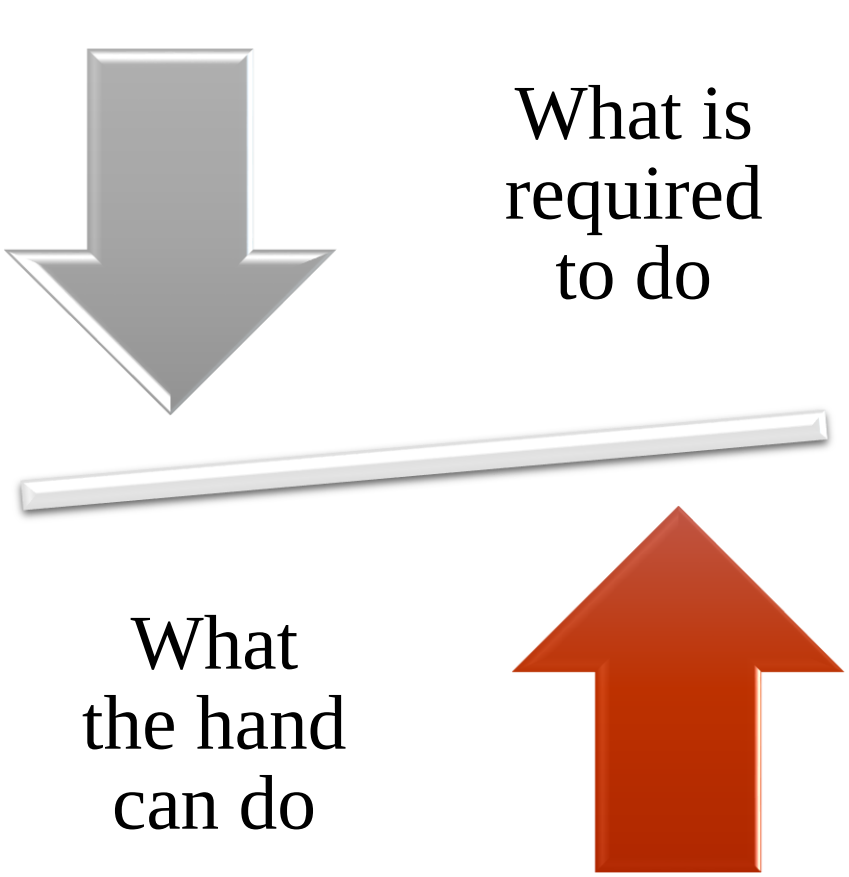


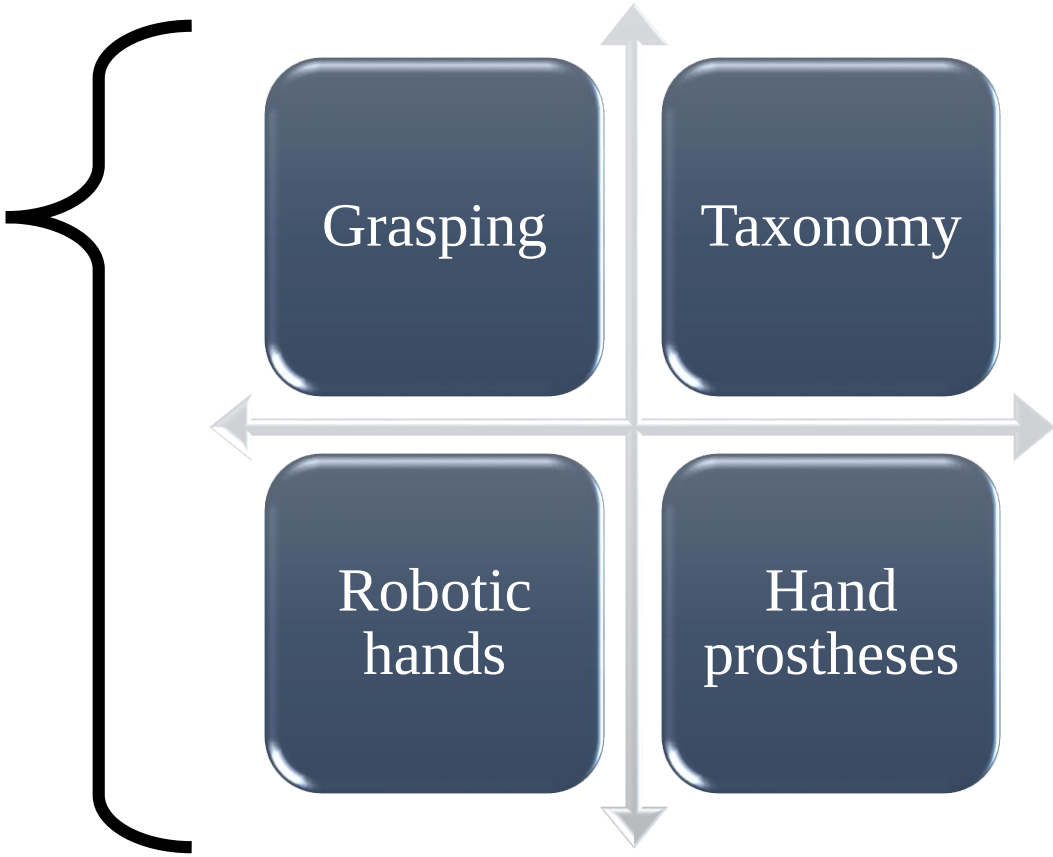
Joint	Finger	1st DoF		2nd DoF		3rd DoF
		flexion [°]	extension [°]	abduction [°]	adduction [°]	Rotation [°]
Wrist	-	85	85	15	45	-
MCP	I	60-90	0	-	-	-
	II	100	30	30	30	-
	III	90	30	30	30	-
	IV	80	30	30	30	-
	V	70	30	30	30	-
PIP	I	80	10	-	-	-
	II-V	90	0	-	-	-
DIP	II-V	90	5	-	-	-
TM	I	60	0	0	60	120

Grasping analysis approach

What is required to do

What the hand can do





Most used grasping gestures

Medium wrap

Light tool

Prismatic
4 fingers

Prismatic
3 fingers

Prismatic
2 fingers

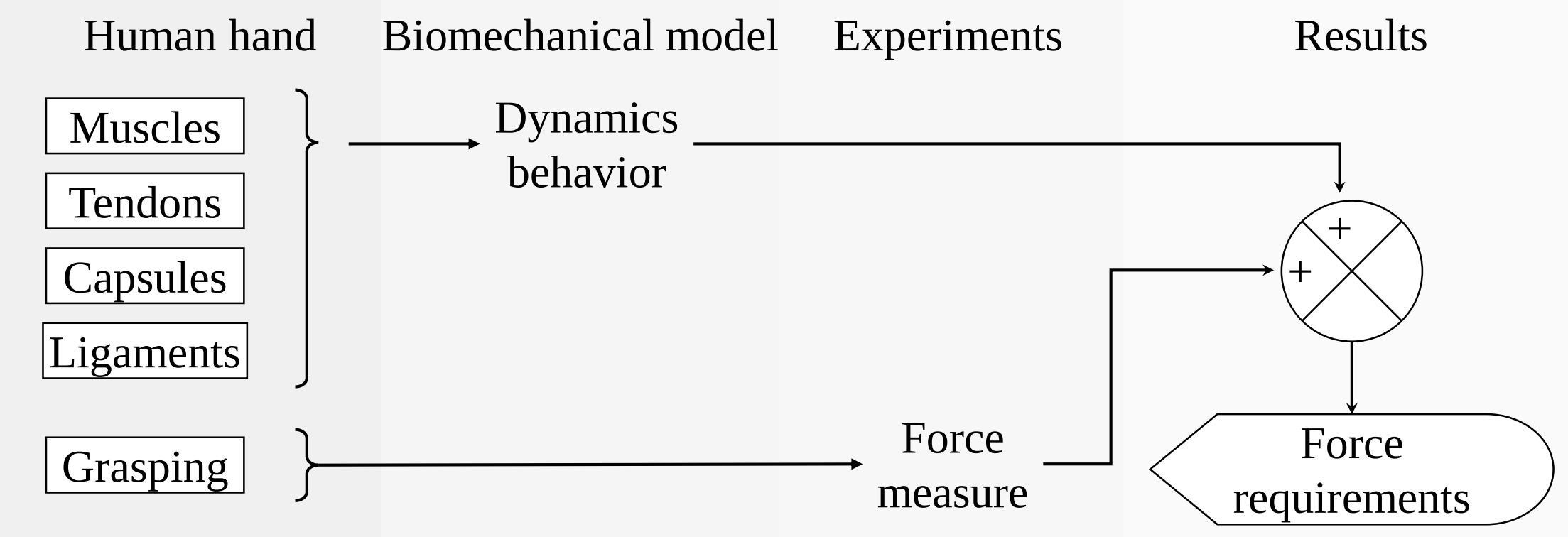
Precision disk

Tripod

Thumb	VF1	VF2	VF3
Rot (Abd)	I	II-III II-V	
Rot (Abd)	I -	II-V	P
Rot (Abd)	I	II-III	

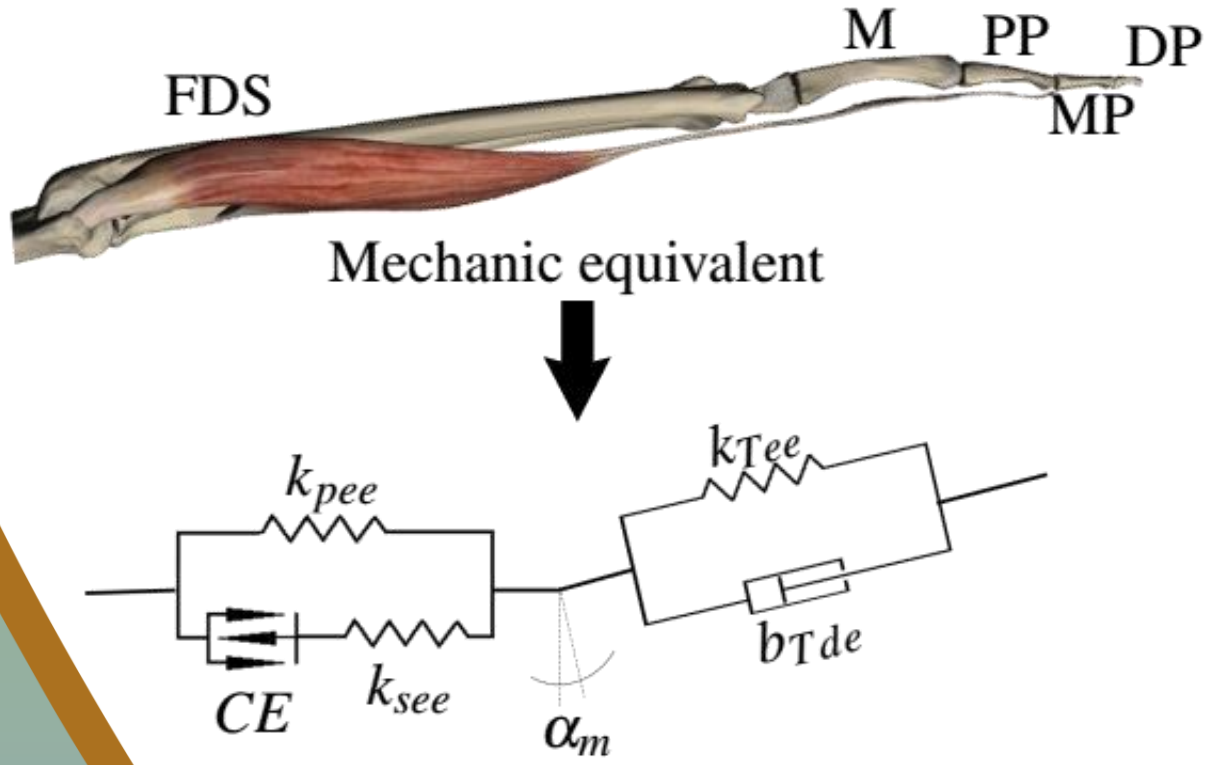
- **Thumb rotated**
- **Three fingers**
- **Fingers II-V have a similar position**

Workflow proposed to identify hand requirements regarding force



New Hill based model

Hill's equivalent models are suitable to qualify the muscle's behavior through the comparison with mechanical elements.



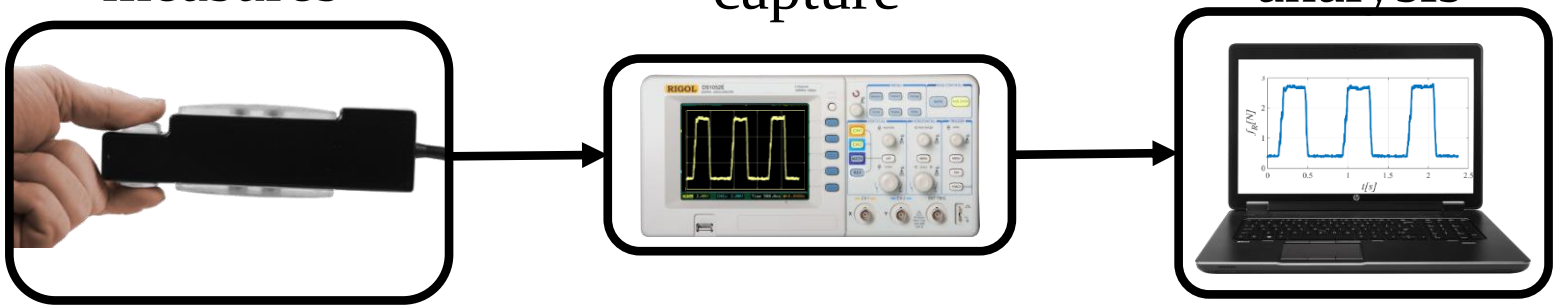
Muscle	CE	:	Contractile element
	k_{pee}	:	Parallel elastic element
	k_{see}	:	Serial elastic element
	α_m	:	Pennation angle
Tendon	k_{Tee}	:	Tendon elastic element
	b_{Tde}	:	Tendon damping element

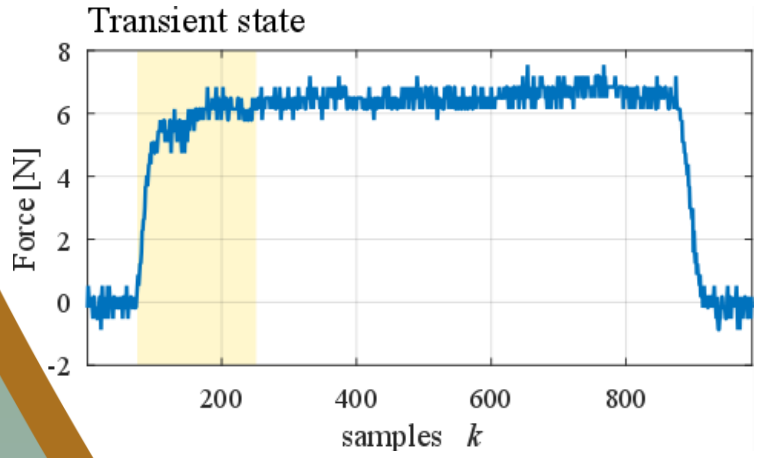
Measure of fingertip force

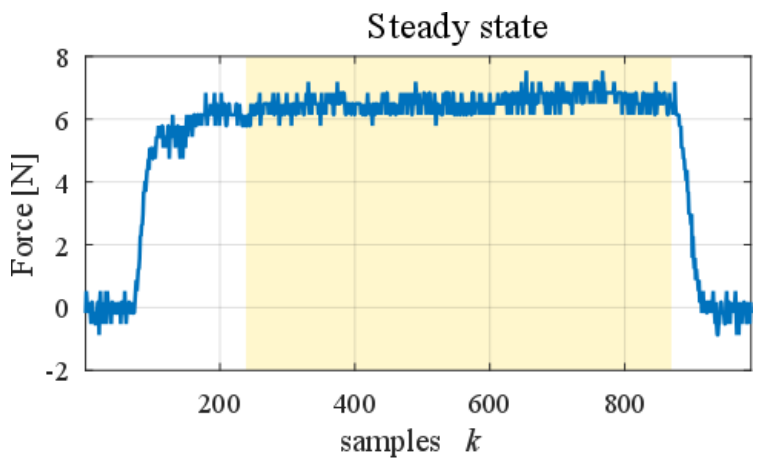
Dynamometric measures

Single signal capture

Mean signal analysis

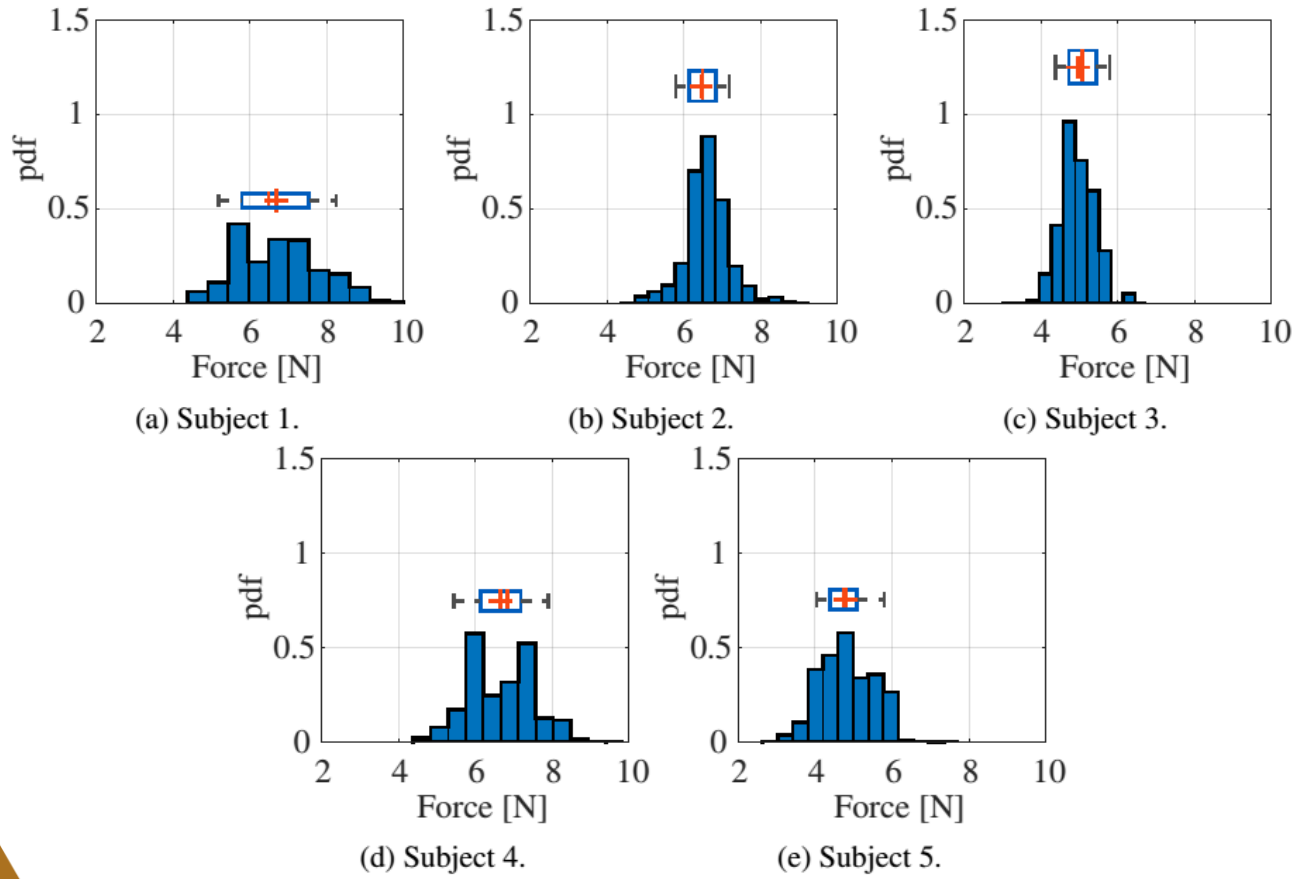






- Five healthy subjects
- Aged between 24 and 30 years old
- Each subject perform five trials
- Trials are followed of 5 min breaks to avoid muscles fatigue

Mean value of the human pinch force



(a) Subject 1. (b) Subject 2. (c) Subject 3.

(d) Subject 4. (e) Subject 5.

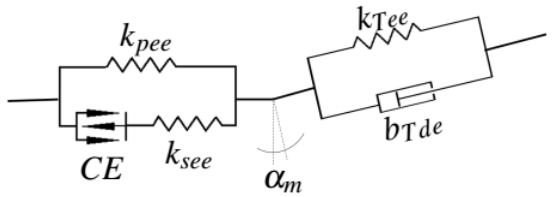
Subject	Mean pinch force [N]	Standard deviation [N]
1	6.70	1.12
2	6.45	0.58
3	4.97	0.48
4	6.66	0.86
5	4.78	0.65

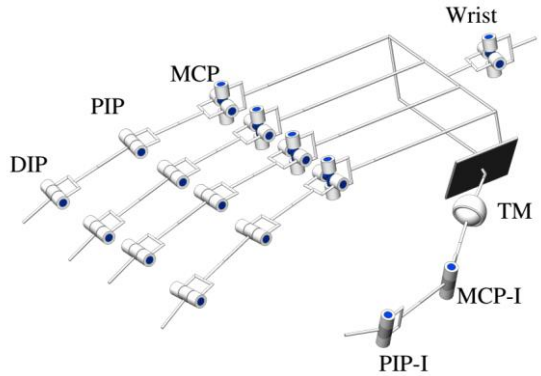
$0.18s < t_s < 0.45s$

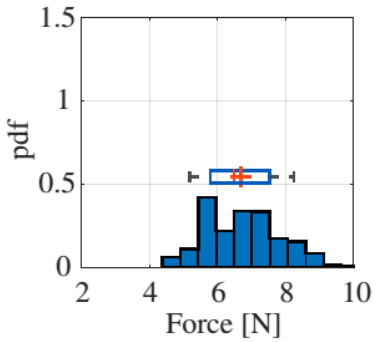
Standard deviation 0.10s

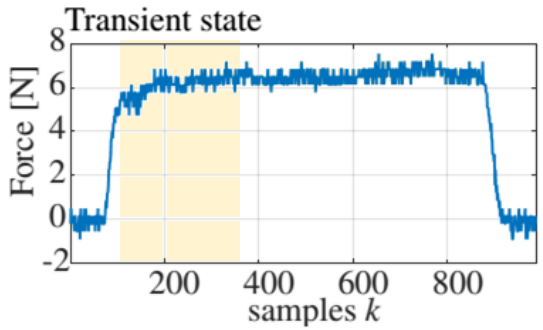
Hand prosthesis requirements

- Merging movements.
- Viscoelastic actuation behavior.
- MCP, PIP, and DIP flexion 90°.
- Fingertip force [4.78N, 6.70N].
- Settling time [0.18s, 0.45s].









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Description of the ProMain-I robotic hand

- **Three fingers:** required for the chosen grasping gestures.
- **Under-actuated:** improve size, weight, and electrical requirements

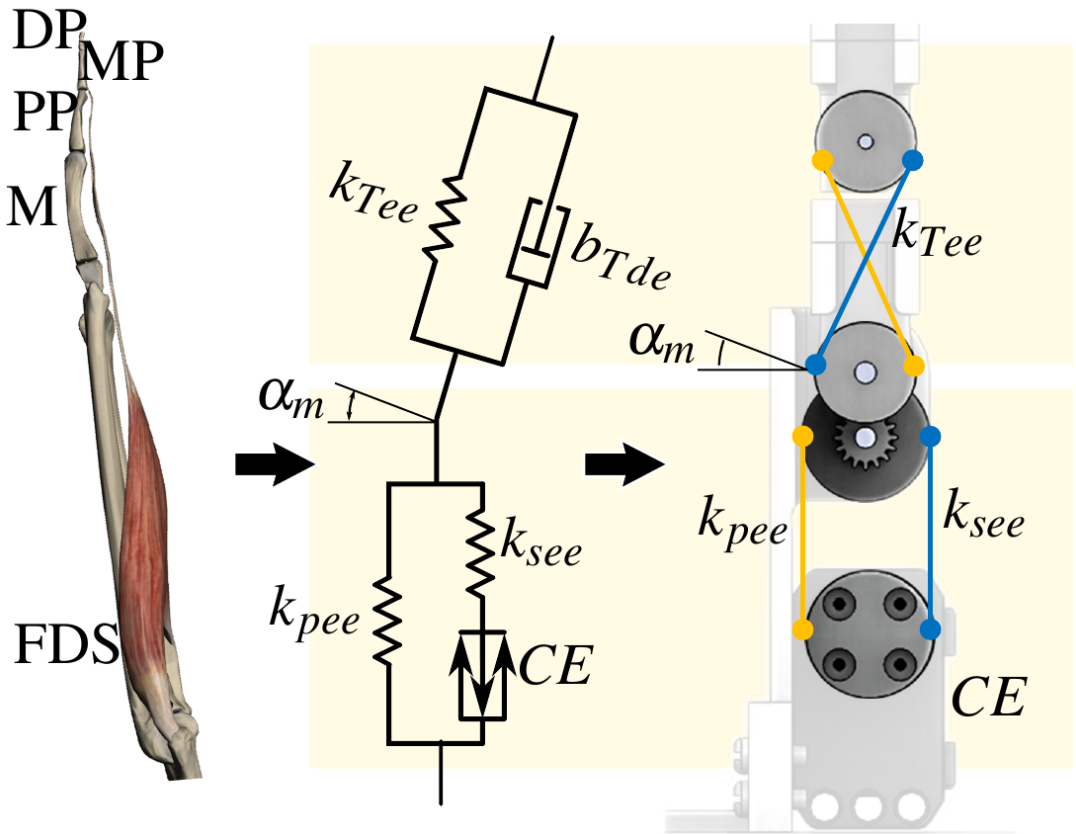
Grasping

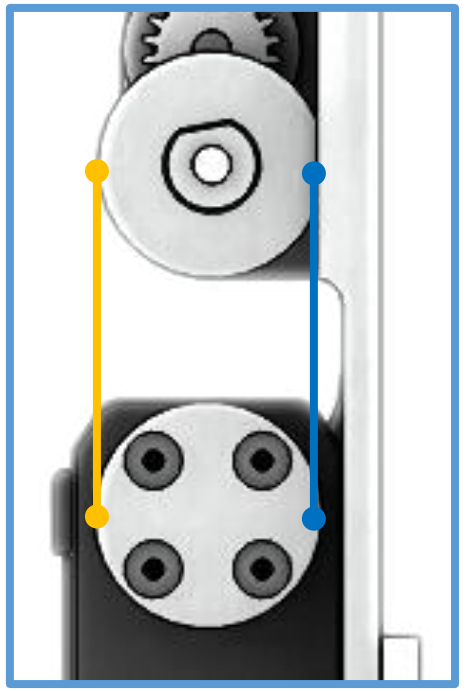
Preparation		Execution	
adduction abduction	passive chassis	flexion extension	active fingers

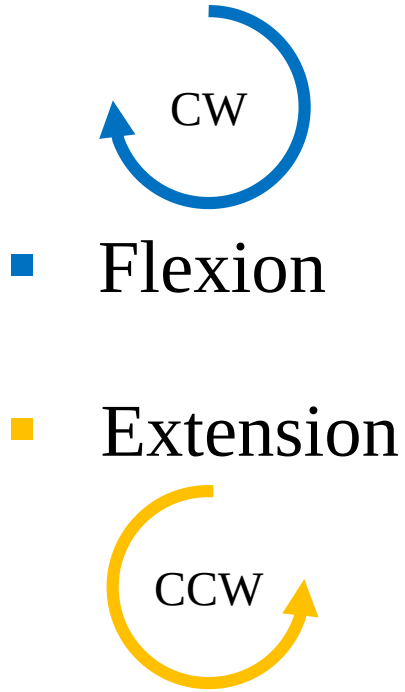
- Thumb is abducted
- Index and middle abduction angle = 15°

- Fingers perform up to 90° rotation during flexion-extension

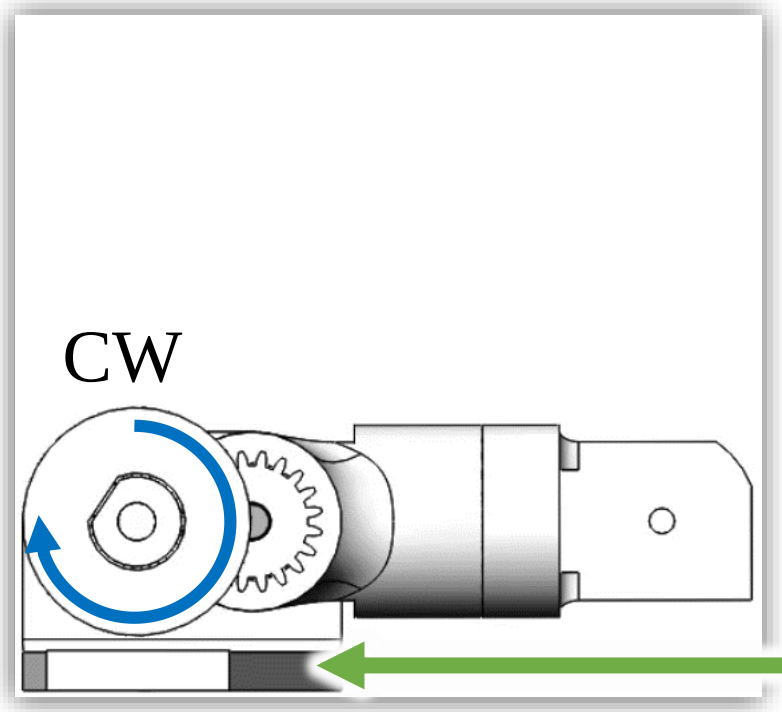
Soft epicyclic mechanism





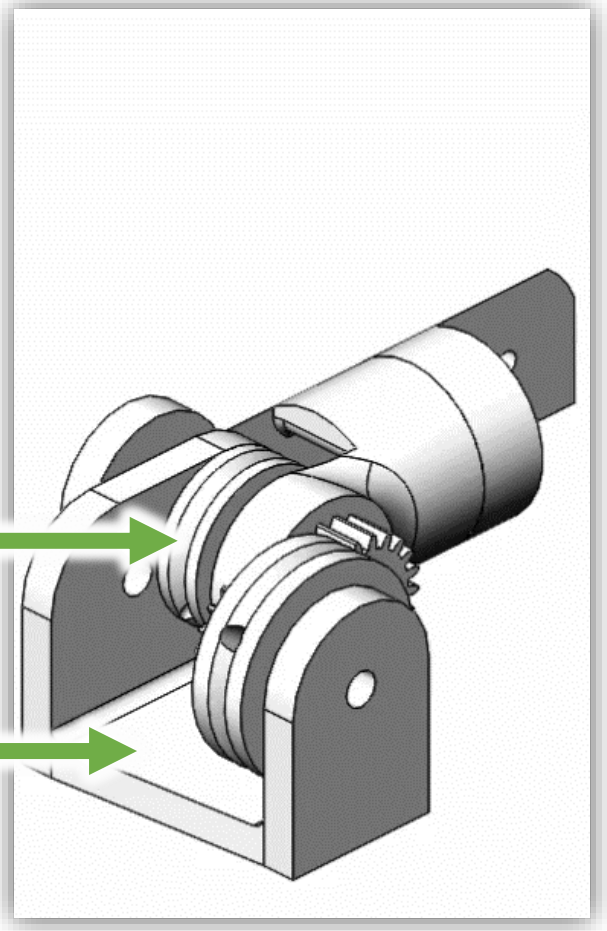


Proximal phalange actuation

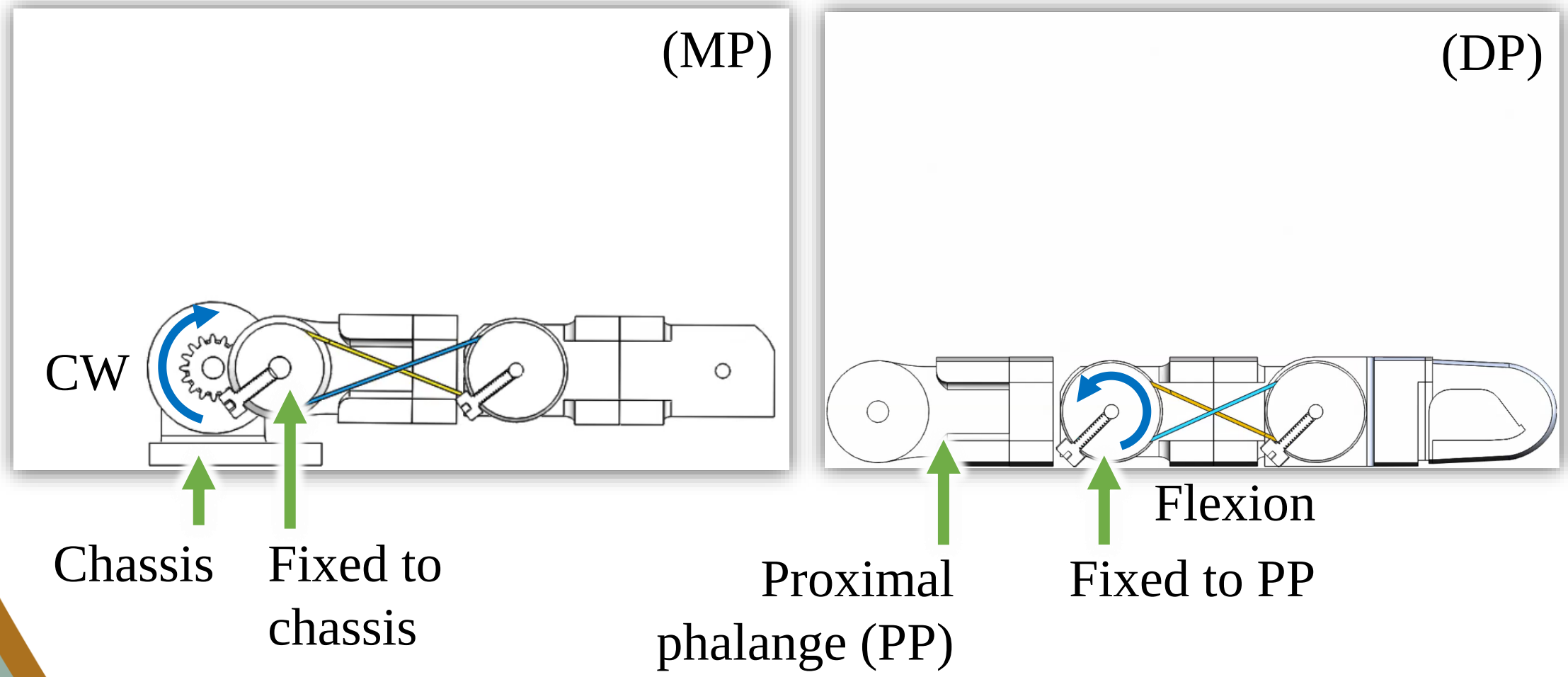


Pulley fixed to chassis

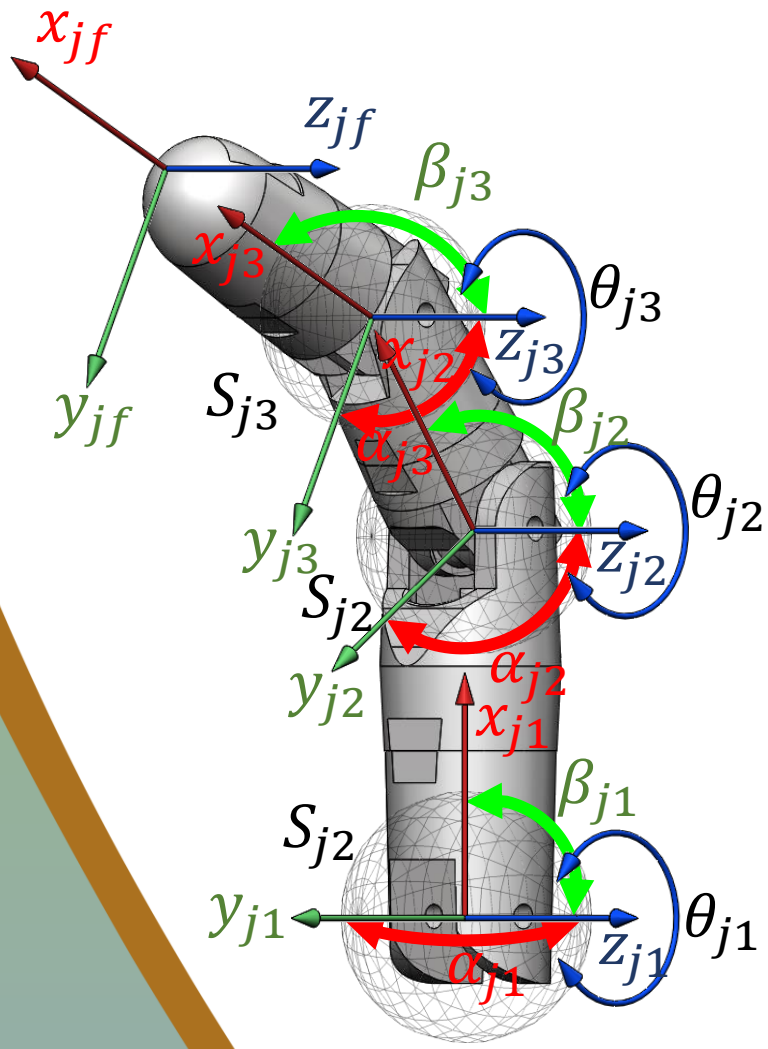
Chassis



Under-actuated movement of medial (MP) and distal (DP) phalanx



New DHKK-SRQ kinematic model



Rotation θ_i around z_i.
Rotation α_i around x_{i-1}.
Translation a_i along of x_{i-1}.
Translation d_i along of z_i.

DHKK Parameterization

+

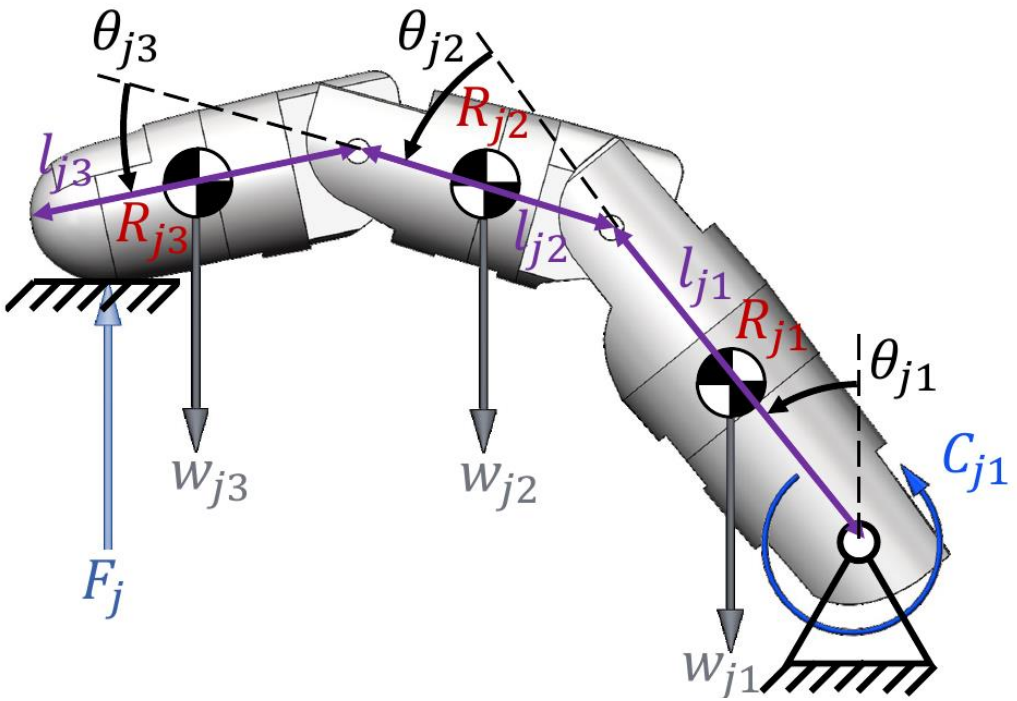
Quaternions formulations

$$\mathbb{U} = [\![\cos(\gamma/2), \vec{u}\sin(\gamma/2)]\!]$$
$$\mathbb{H} = [\![0, \vec{h}]\!]$$
$$[\![0, \vec{h}']\!] = [\![\mathbb{U}\,\mathbb{H}\,\overline{\mathbb{U}}]\!]$$

- **Improves** the **representation of rotations** that arise from soft robotics.
- Do not require to increase **model size** to formulate extra rotations.
- Formulate soft robot's rotations even in **the neighborhood of rotational singularities.**

(Ramirez *et al.*, 2015)

Dynamic model



$$C_{j1}(F_j, \{q\}, \{\dot{q}\}, \{\ddot{q}\})$$

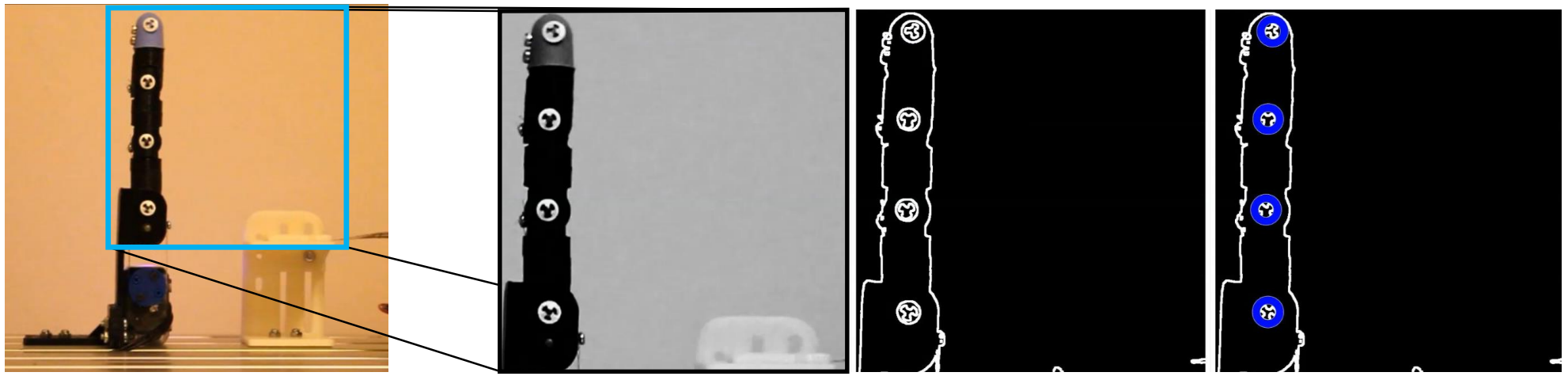
External forces

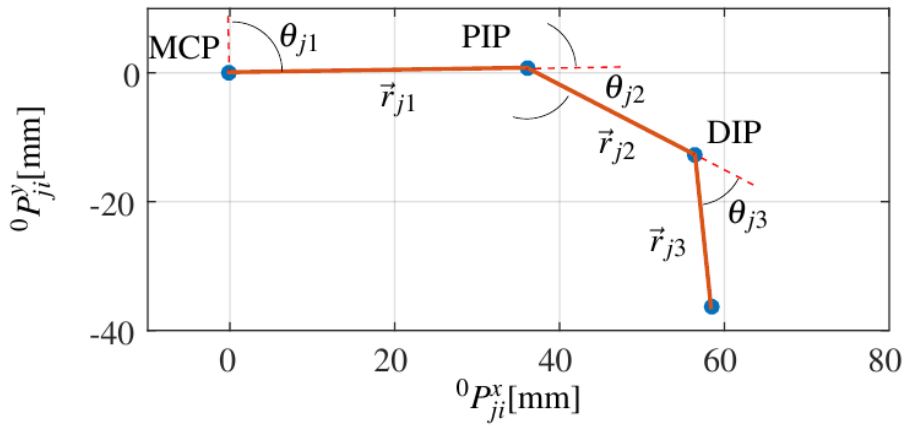
$$\{\delta W_e\} = \{Q_e\}^T \{\delta r_e\}$$

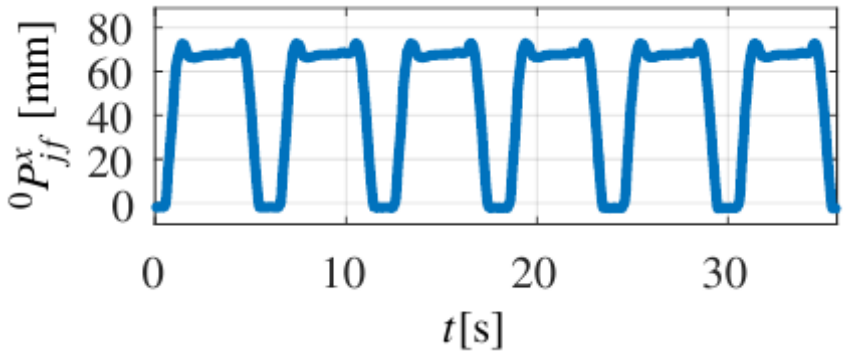
$$\{\delta W_\lambda\} = ([M]\{\ddot{q}\})^T \{\delta r_\lambda\}$$

Inertial forces

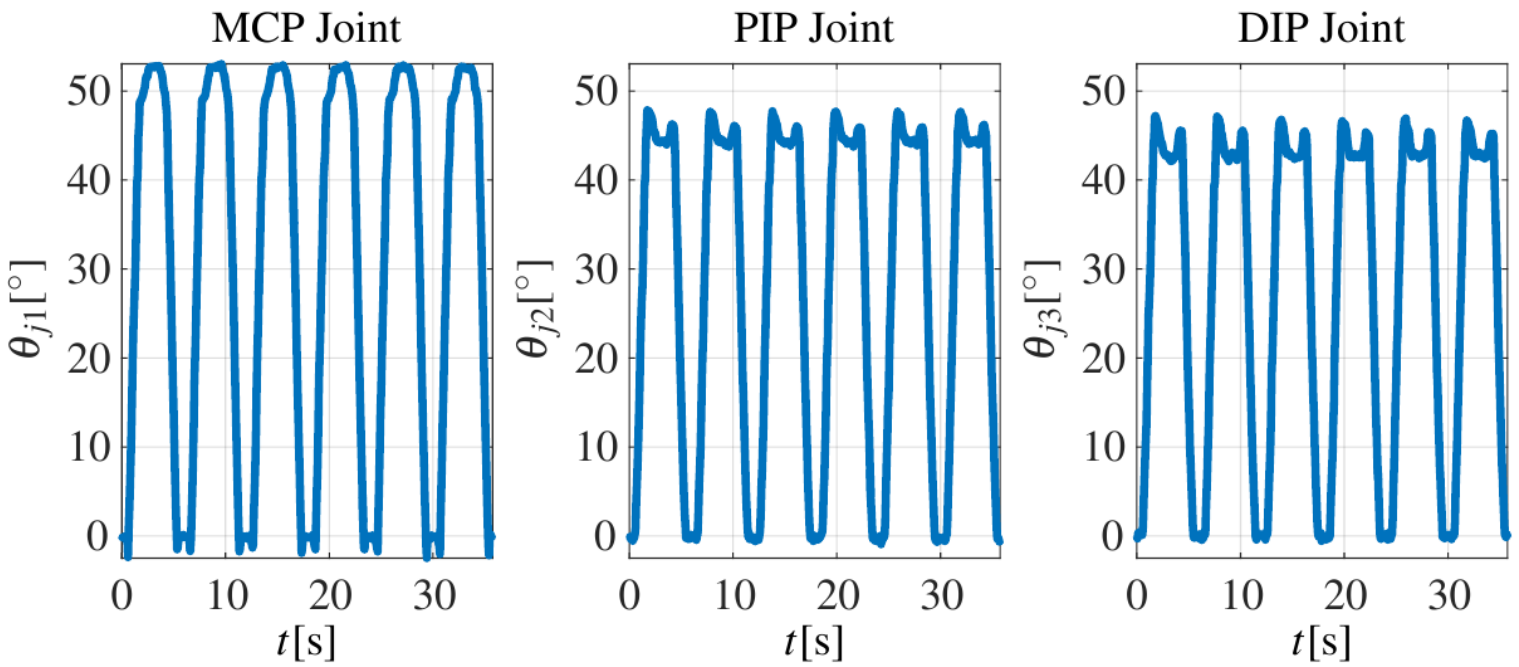
Position tracking



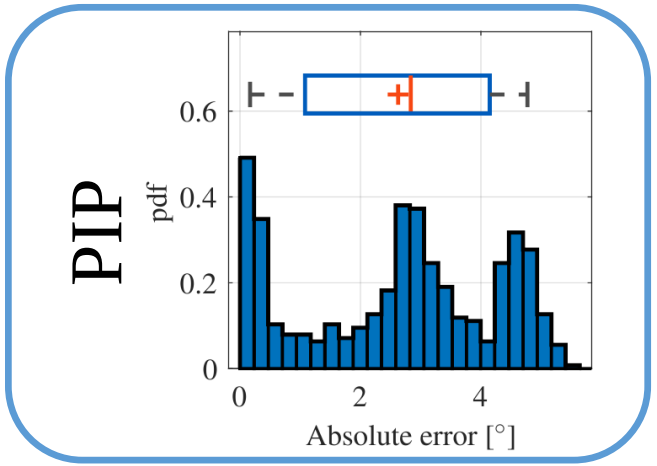


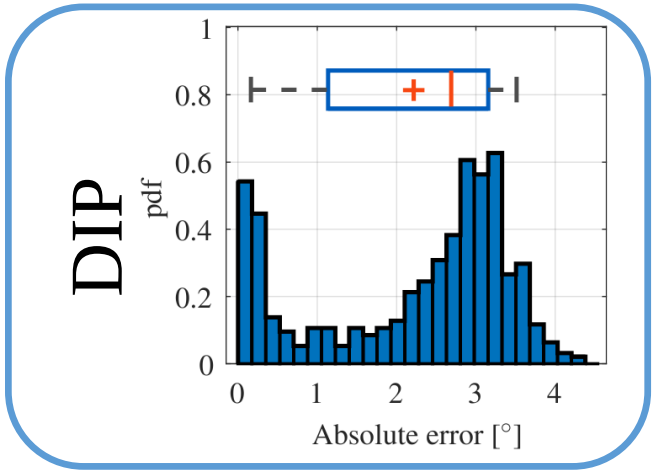


Joint rotation analysis

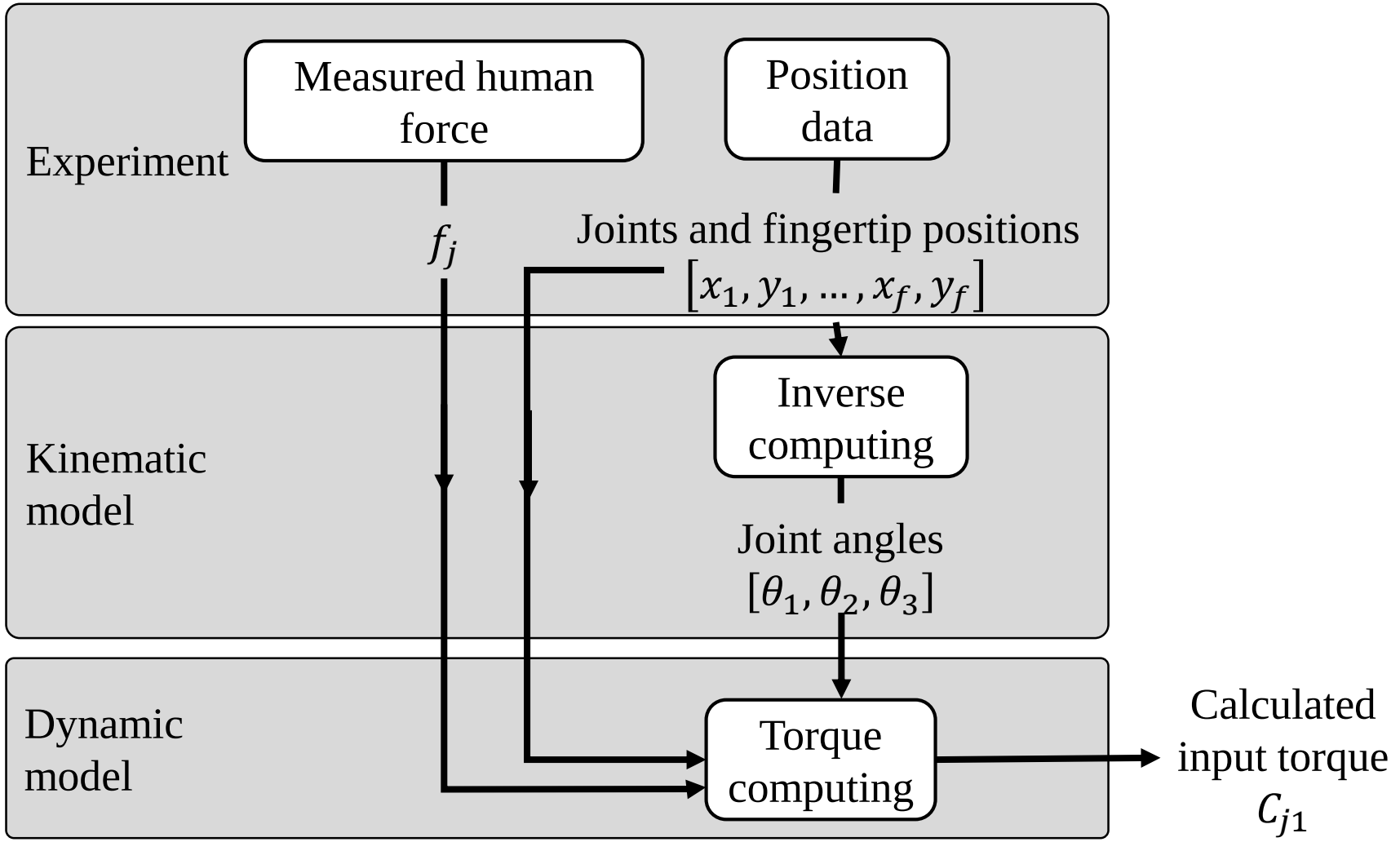


$$\theta_{j2} = \theta_{j3} = 0.9\,\theta_{j1}$$



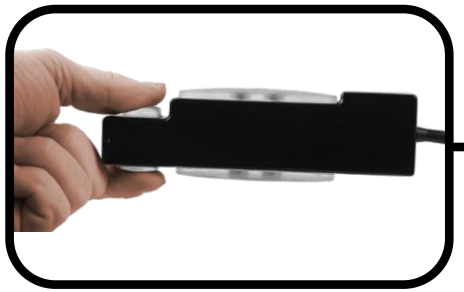


Actuation requirements definition

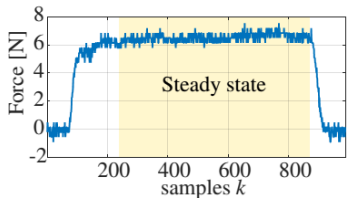


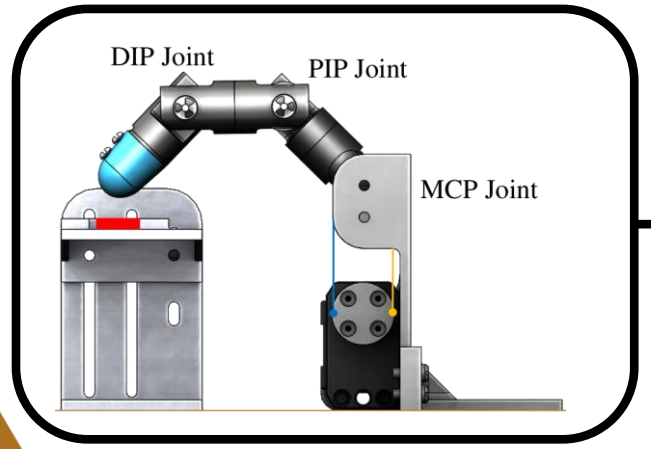
Actuation requirements

Dynamometric Measures

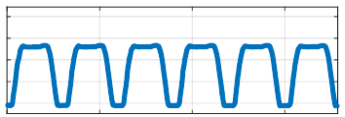


$4.78\text{N} \leq F_j \leq 6.70\text{N}$

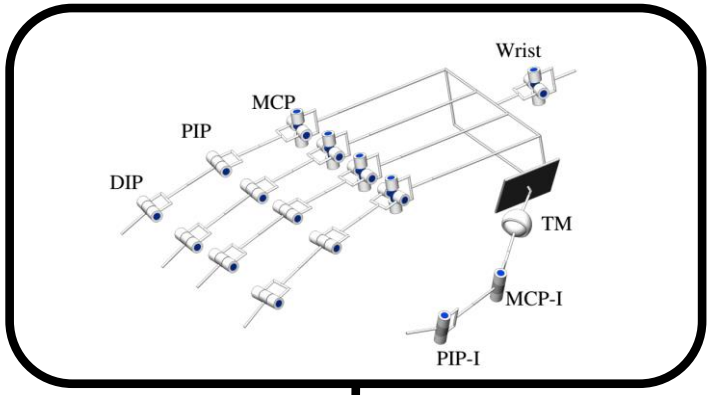




$\{q\}, \{\dot{q}\}, \{\ddot{q}\}$



Kinematic + Dynamic



Settling time: [0.18s, 0.45s]
Joint rotation: 90°

Torque: [124.7Nmm,175.8Nmm]

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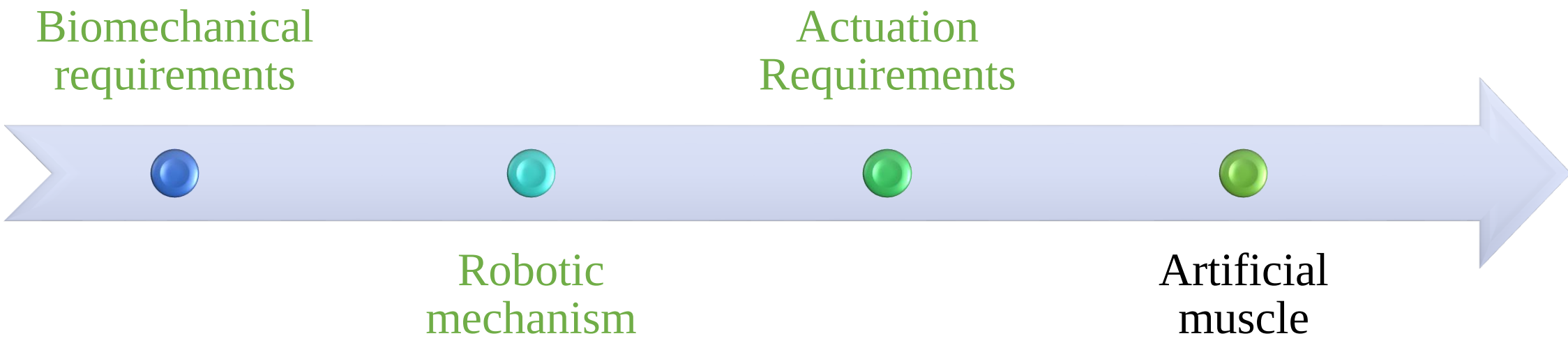
5. Conclusions and perspectives

Artificial muscle design methodology

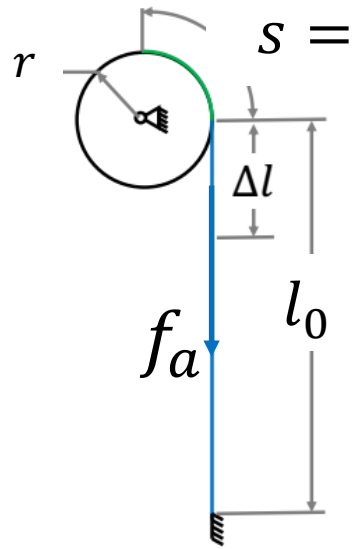


Ionic Polymer Metal Composite (IPMC)
Electrolyte gels (E. gels)
Conductive Polymers (CPs)
Piezoelectric Ceramics (PCs)

Rheological Fluids (R. Fluids)
Electronic ElectroActive Polymers (E. EAP)
Shape Memory Alloys (SMAs)

Smart material actuation principle

Elongation (E) based



$$s = r\theta_{j1}$$

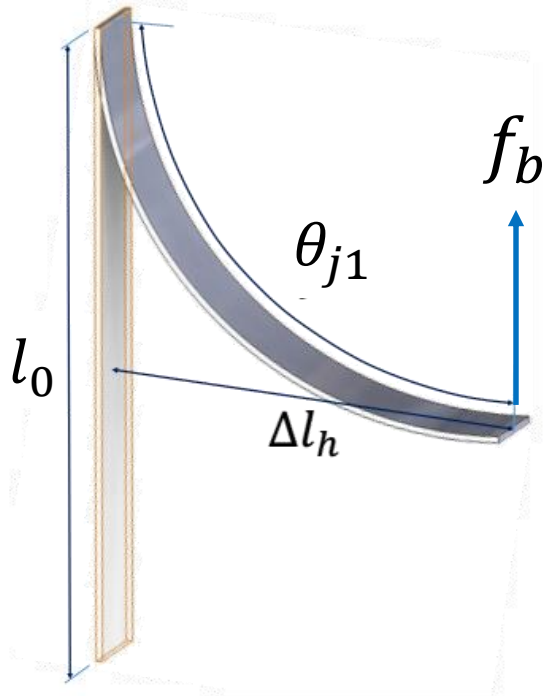
$$\varepsilon_a = \frac{\Delta l}{l_0}$$

$$r = 7mm$$

$$124.7\text{Nmm} \leq C_{j1} \leq 175.8\text{Nmm}$$

$$\varepsilon_a \geq 0.045 \quad 17.8\text{N} \leq f_a \leq 25.1\text{N}$$

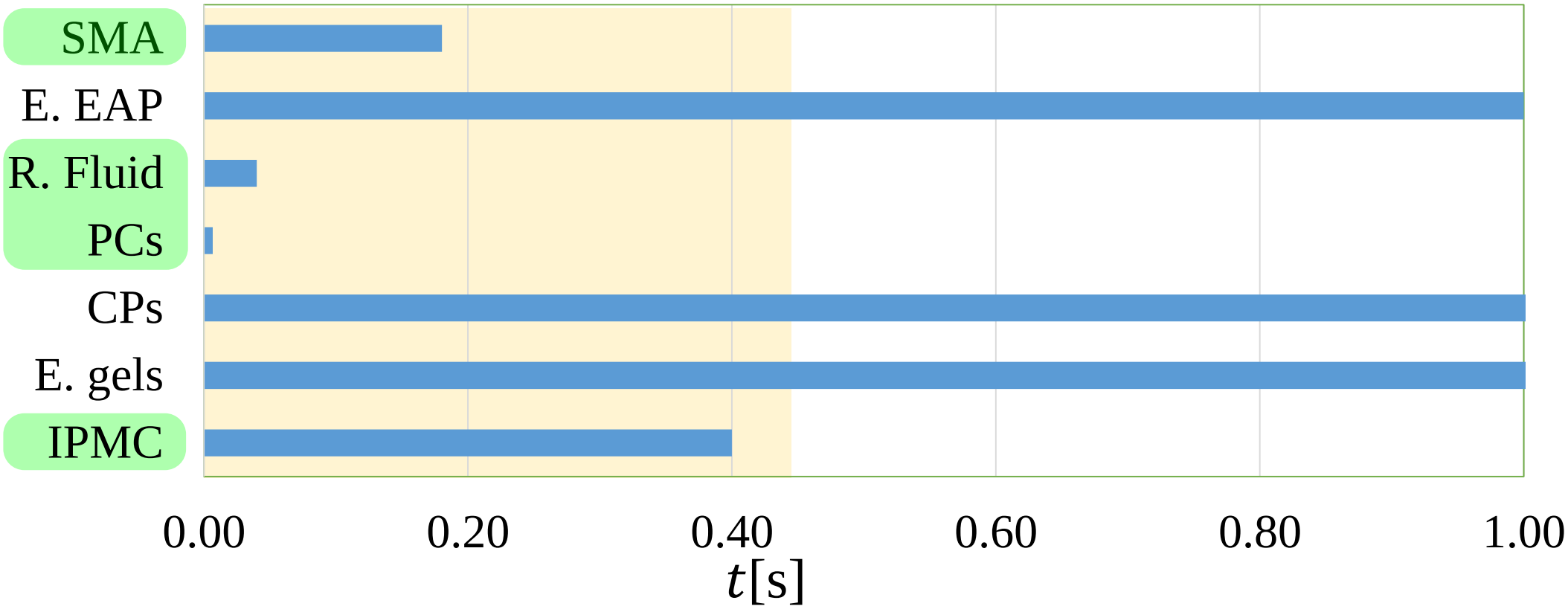
Bending (B) based



$$\varepsilon_b = \frac{\Delta l_h}{l_0}$$

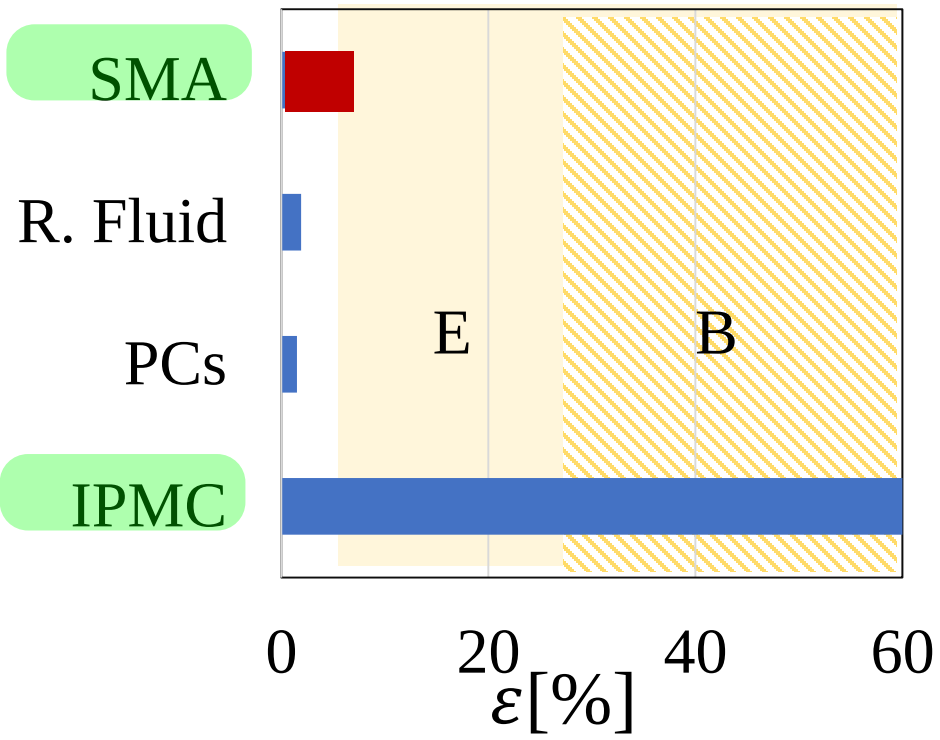
$$\varepsilon_b \geq 0.5 \quad 4.8\text{N} \leq f_b \leq 6.7\text{N}$$

Settling time of smart materials



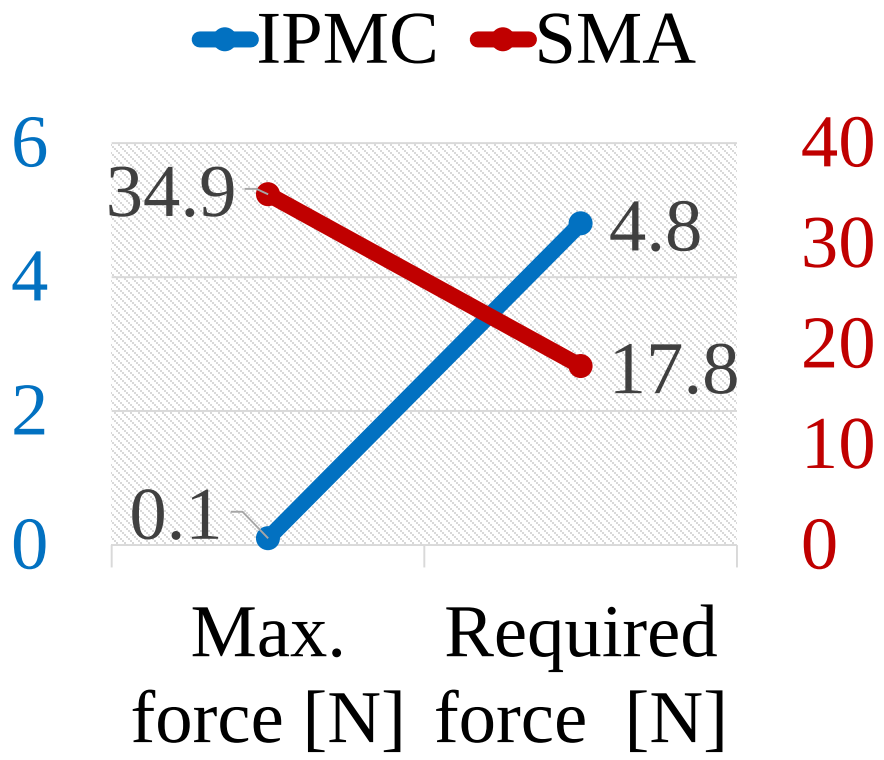
[0.18s, 0.45s]

Active strain and actuation force comparison



$\varepsilon_a \geq 4.5\%$

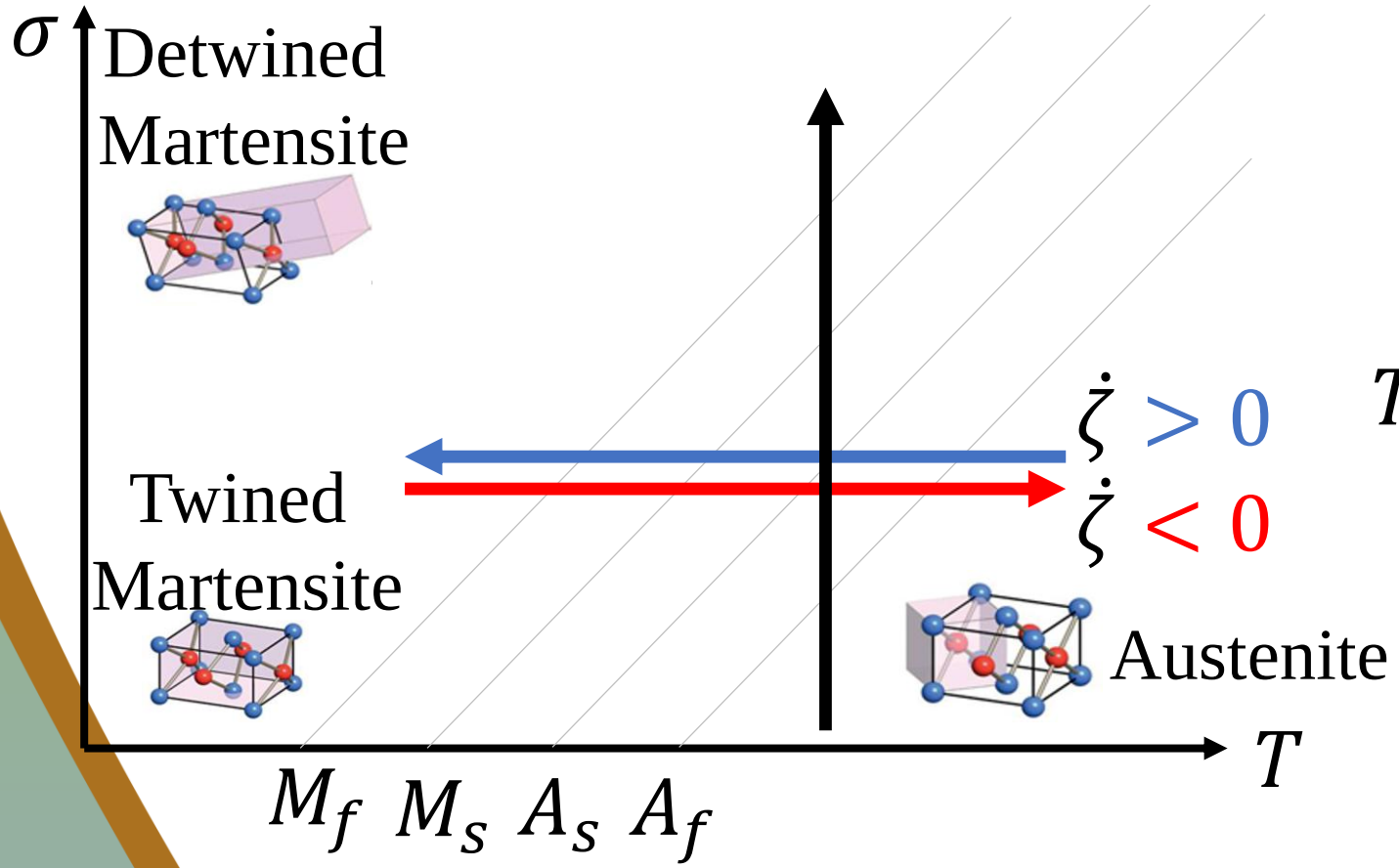
$\varepsilon_b \geq 50\%$

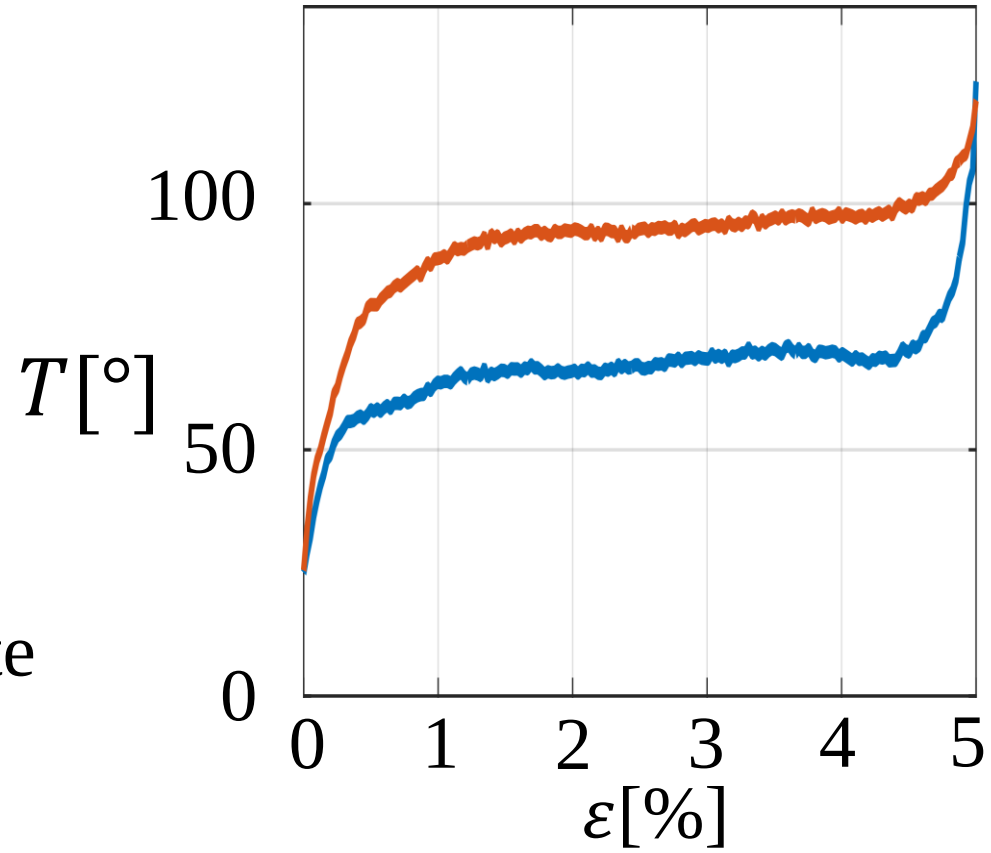


$17.8\text{N} \leq f_a \leq 25.1\text{N}$

$4.8\text{N} \leq f_b \leq 6.7\text{N}$

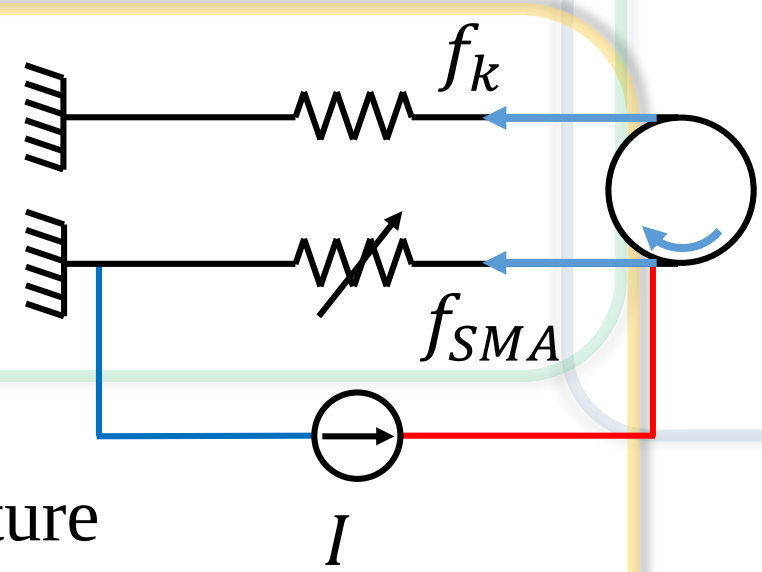
SMA phase transformation



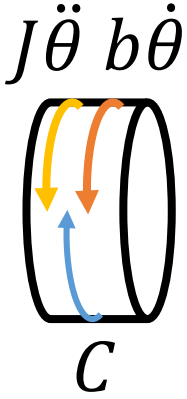


SMA-based actuator modeling

Constitutive model of SMA

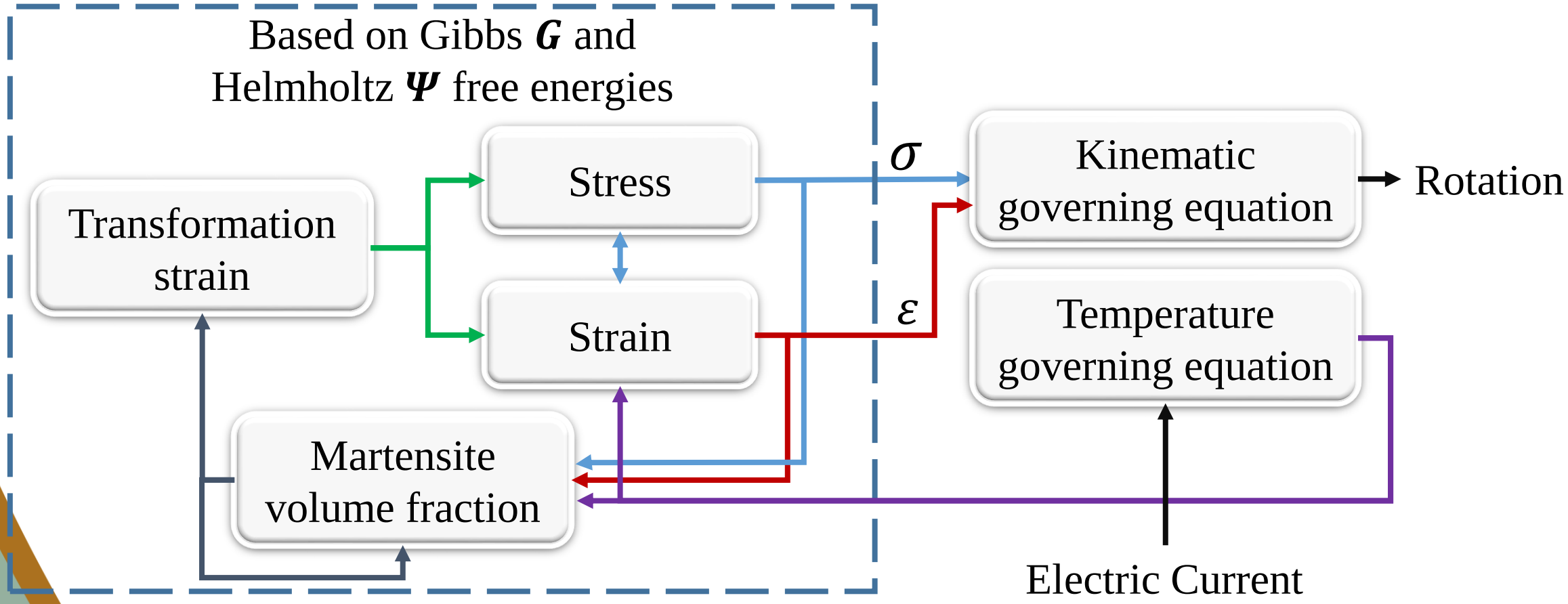


Temperature governing equation

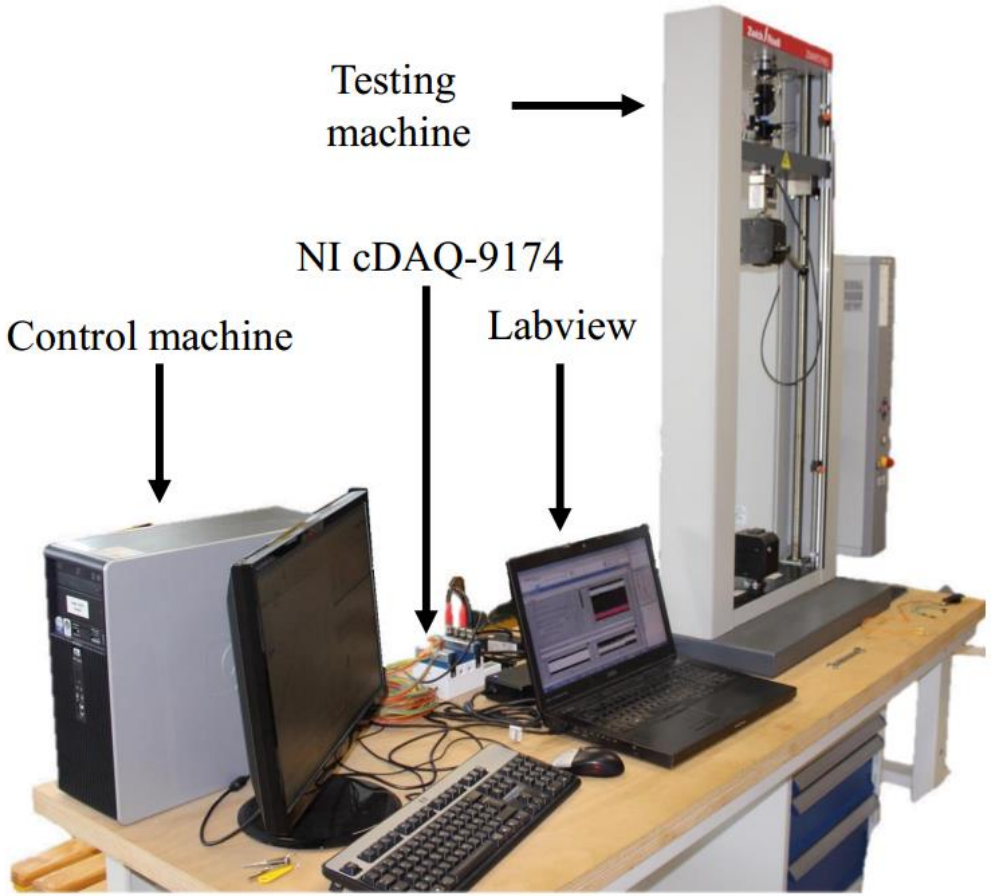


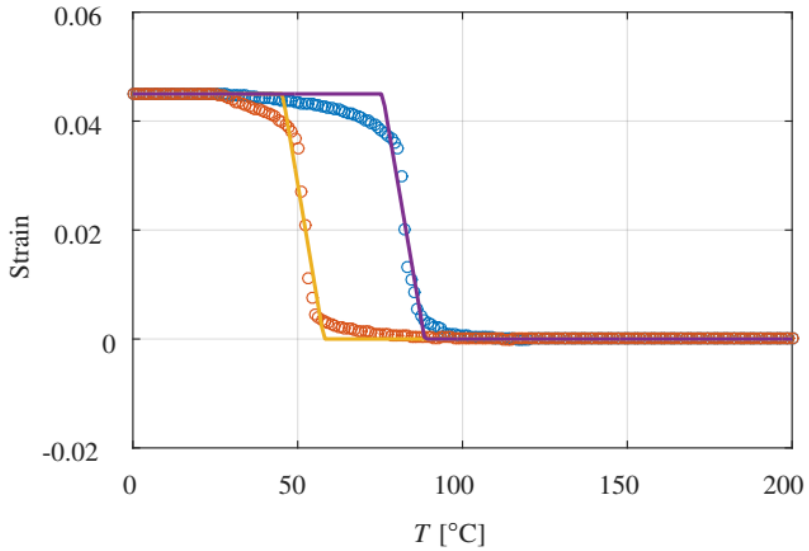
Kinematic governing equation

Constitutive model of SMA



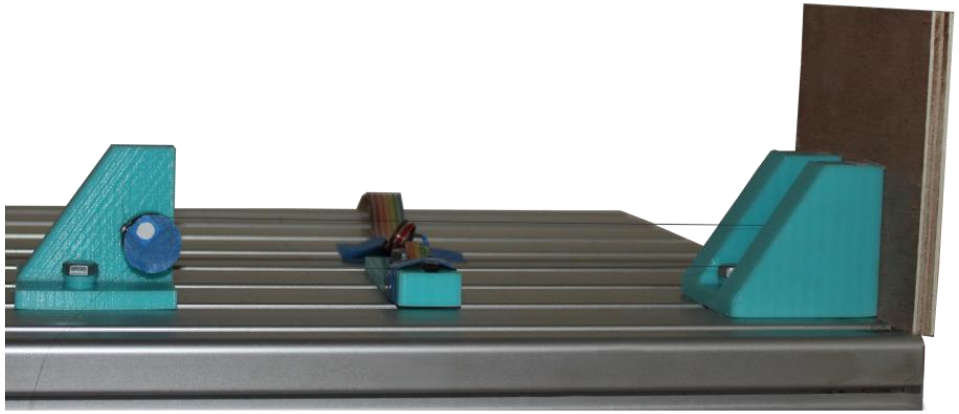
Experiment for measuring parameters

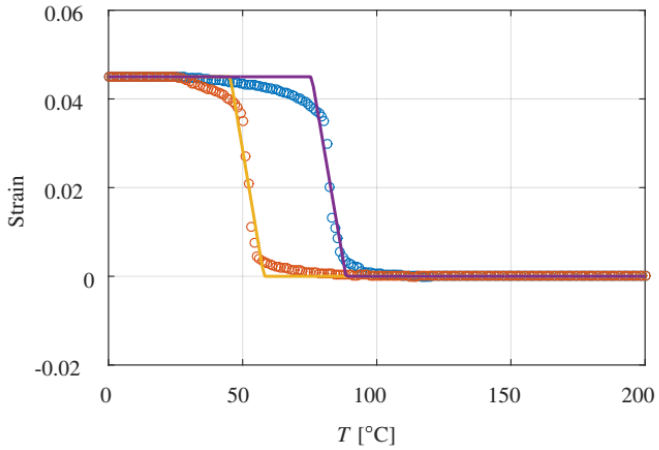


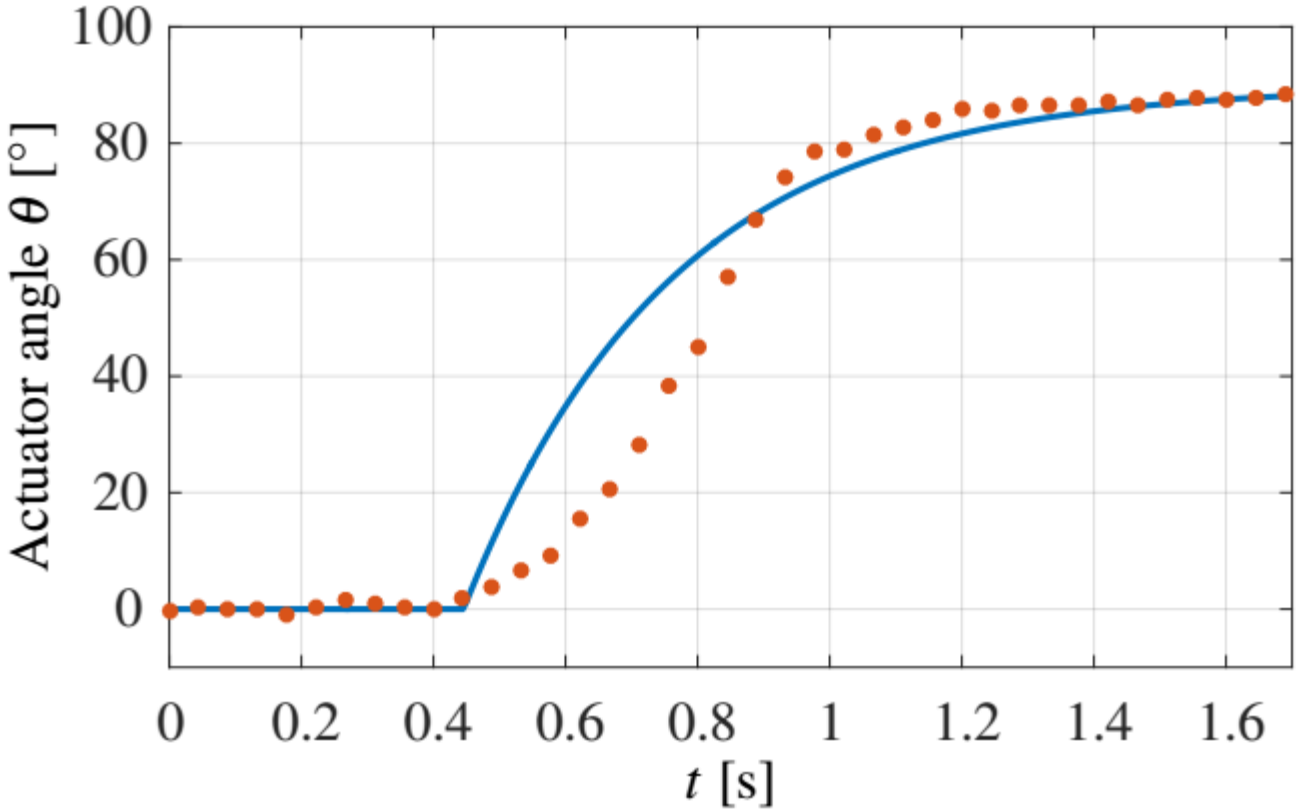


Manufacturer	ρ, α^A, α^M
Measured	E^A, E^M
Identified	$\Delta s_0, M_s, M_f, A_s, A_f$

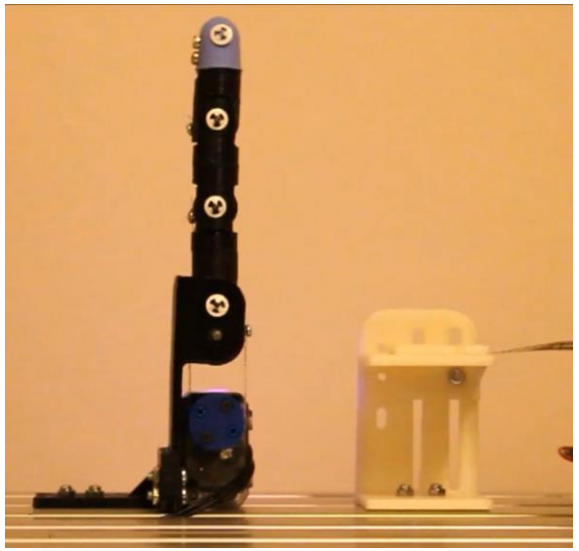
Simulation vs experimental results

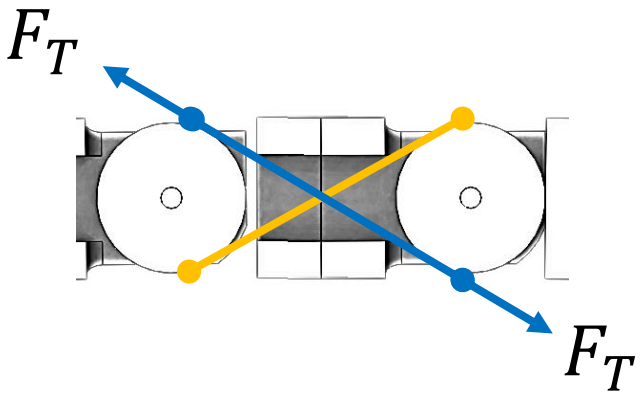


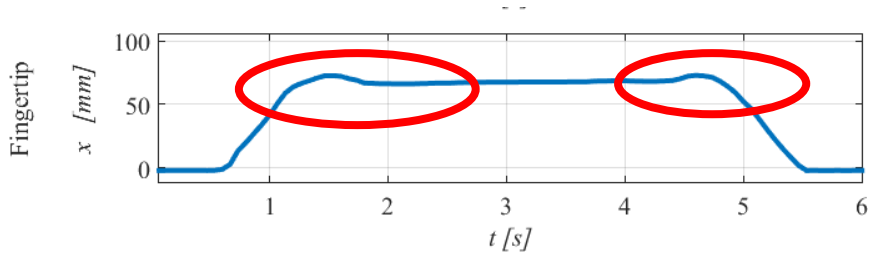


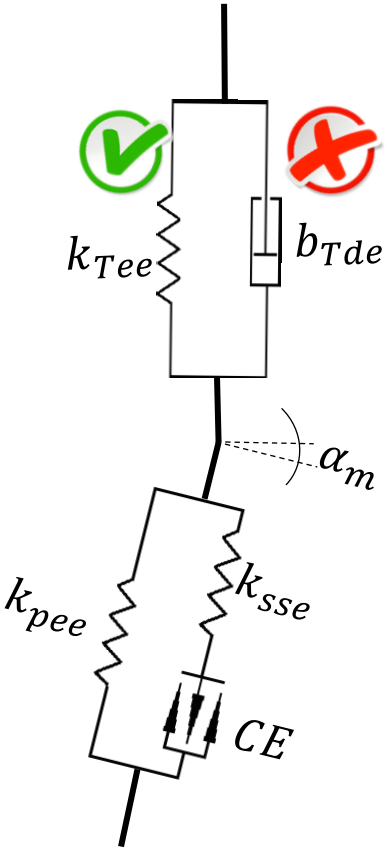


Stiffness control requirement

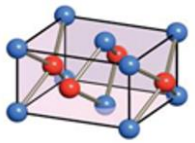


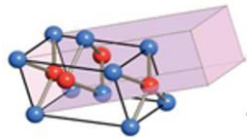


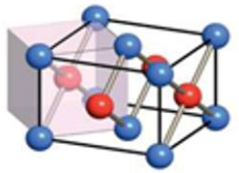


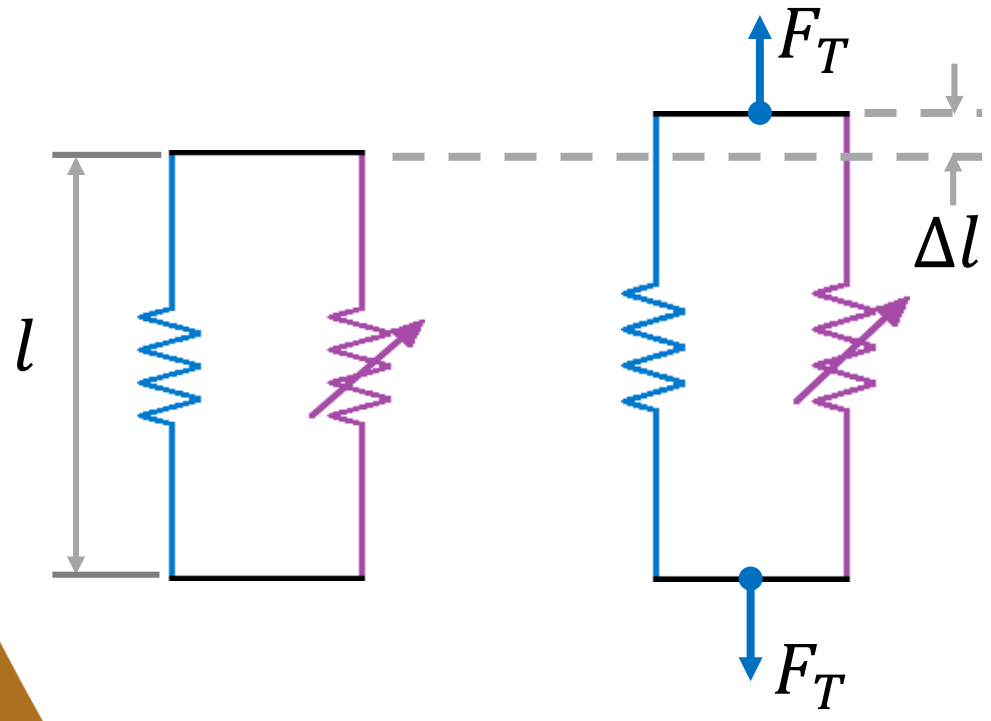


Tendon operating principle

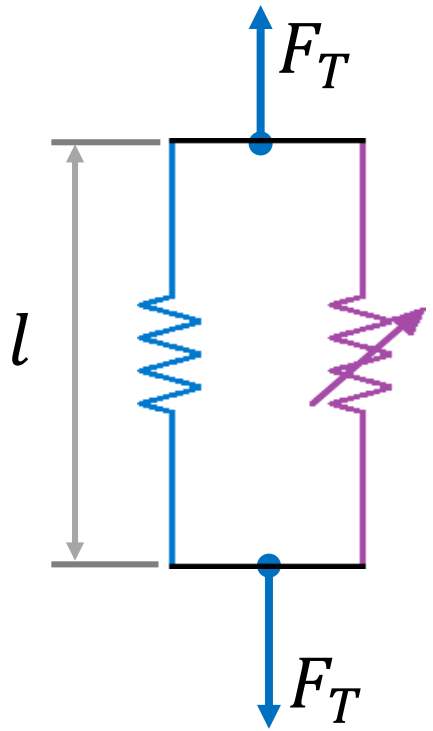
Twinned martensite 

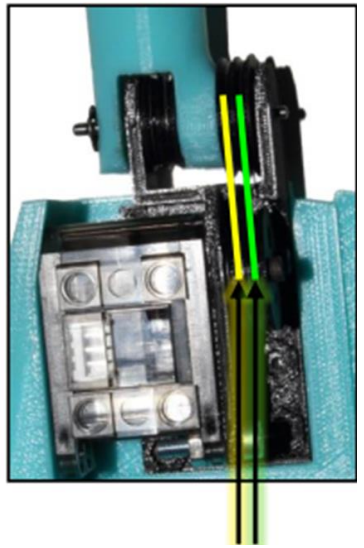
Detwinned Martensite 

Austenite 



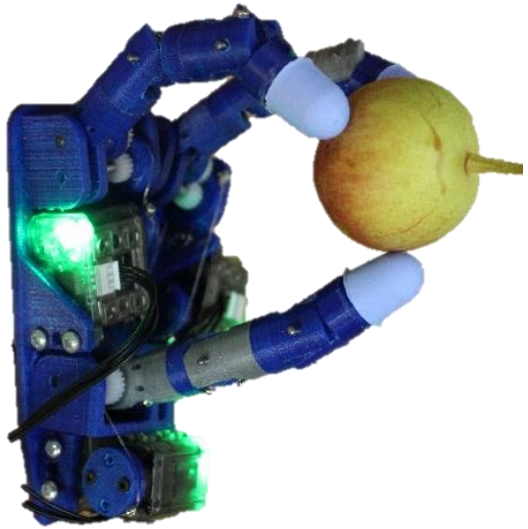
$T = f(u, i, t)$



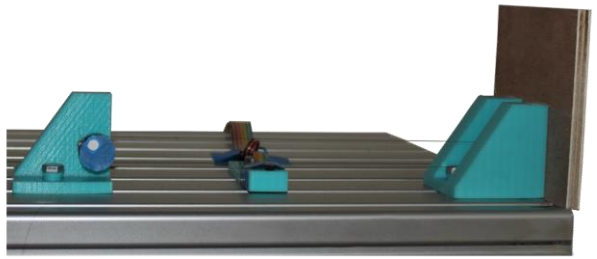


- SMA wire
- Flexion tendon

Current state of the research



- Definition of actuation requirements
- New soft epicyclic mechanism



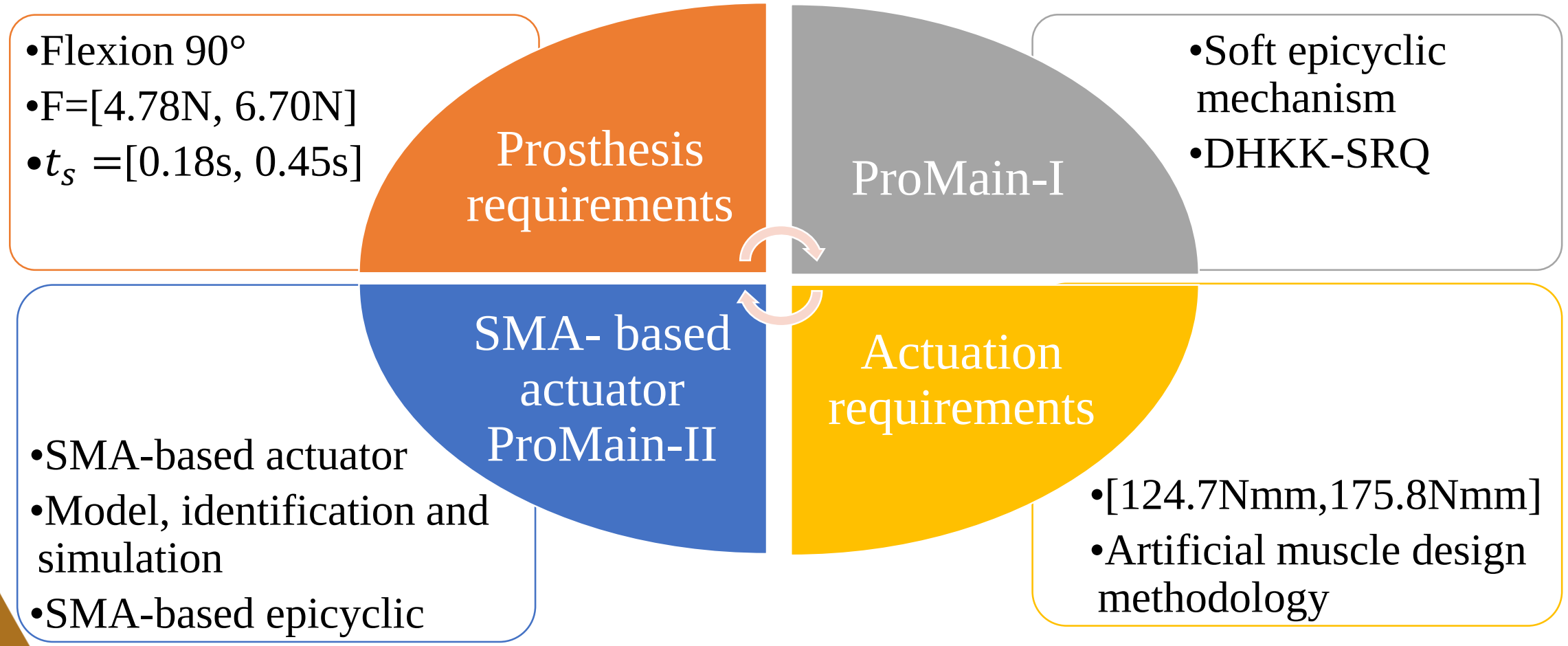
- New SMA-based actuator

- SMA-based soft epicyclic mechanism

Outline

1. Introduction
2. Analysis of the human hand
3. The ProMain-I Prosthesis
4. SMA based artificial muscle
5. Conclusions and perspectives

Conclusion



Hand mechanism, FR 1656914, Jul 2016

Soft kinematic link, FR 1656673, Jun 2016

Soft fingertip force sensor, FR 1655991, Jun 2016

Perspectives

DHKK-SRQ	• Test and validation in 3D • Test ProMain-II using motion capture laboratory.
SMA-based soft epicyclic mechanism	• Quantify the advantage of stiffness control
Smart materials	• Modeling and assessment of IPMCs to improve hand mechanism • Development of a hybrid actuation system using IPCMs

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Development of an artificial muscle for a soft robotic hand prosthesis

Thank You

9 December 2016

Energétique Mécanique Electromagnétisme

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