EMI 2023 INTERNATIONAL CONFERENCE
Engineering Mechanics Institute
2023 International Conference
Palermo
August 27-30, 2023
Università degli Studi di Palermo

A multiscale approach to design of seismic metaisolators

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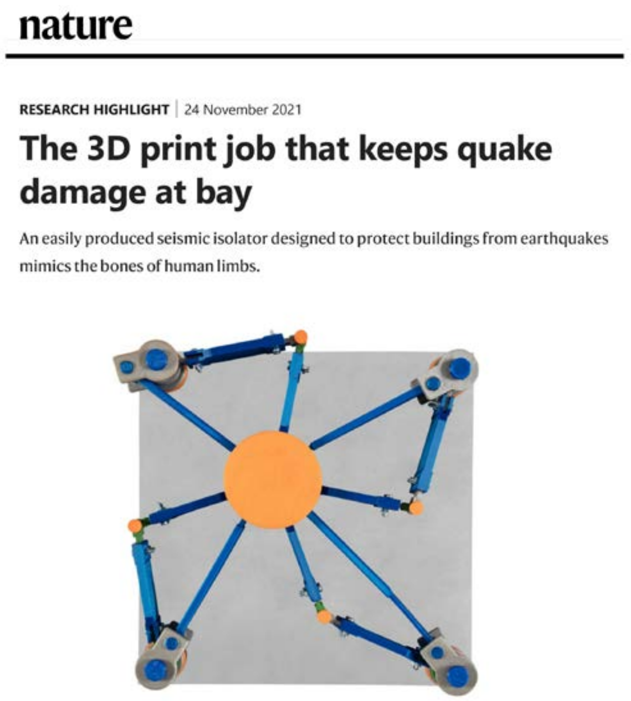
Ministry of Foreign Affairs and International Cooperation

This work was supported by the Italian Ministry of Foreign Affairs and International Cooperation”, grant number US23GR15

OUTLINE

- **Introduction**
- **Novelty/Objective**
- **Materials and methods**
  - **Unit cell design**
  - **Fabrication of physical models**
  - **Experimental validation procedure**
- **Mechanical modeling**
  - **Pseudo-elastic response of the tendons**
  - **Overall mechanical modeling**
  - **Results and discussions**
- **Concluding remarks and future work**


nature

RESEARCH HIGHLIGHT | 24 November 2021

The 3D print job that keeps quake damage at bay

An easily produced seismic isolator designed to protect buildings from earthquakes mimics the bones of human limbs.

Main publications:

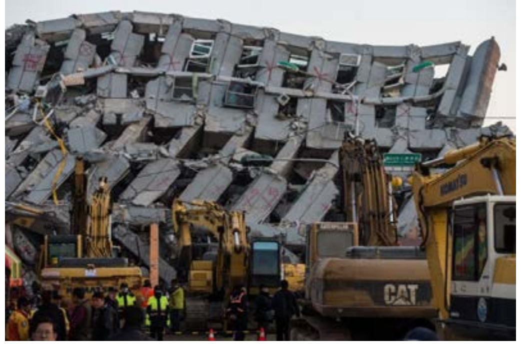
- Fraternali, F., Singh, N., Amendola, A., Benzoni, G., Milton, G.W. A biomimetic sliding–stretching approach to seismic isolation. NONLINEAR DYNAMICS, 106(4), 3147-3159, 2021

- Fraternali, F., Singh, N., Amendola, A., Benzoni, G., Milton, G.W. The 3D print job that keeps quake damage at bay. NATURE 600(7887), 10.

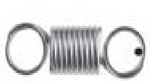
- Fraternali, F., Singh, N., Amendola, A., Benzoni, G., & Milton, G. W. A scalable approach to the design of a 3d-printable sliding-stretching seismic isolator. INGEGNERIA SISMICA, 38(4), 2021

INTRODUCTION

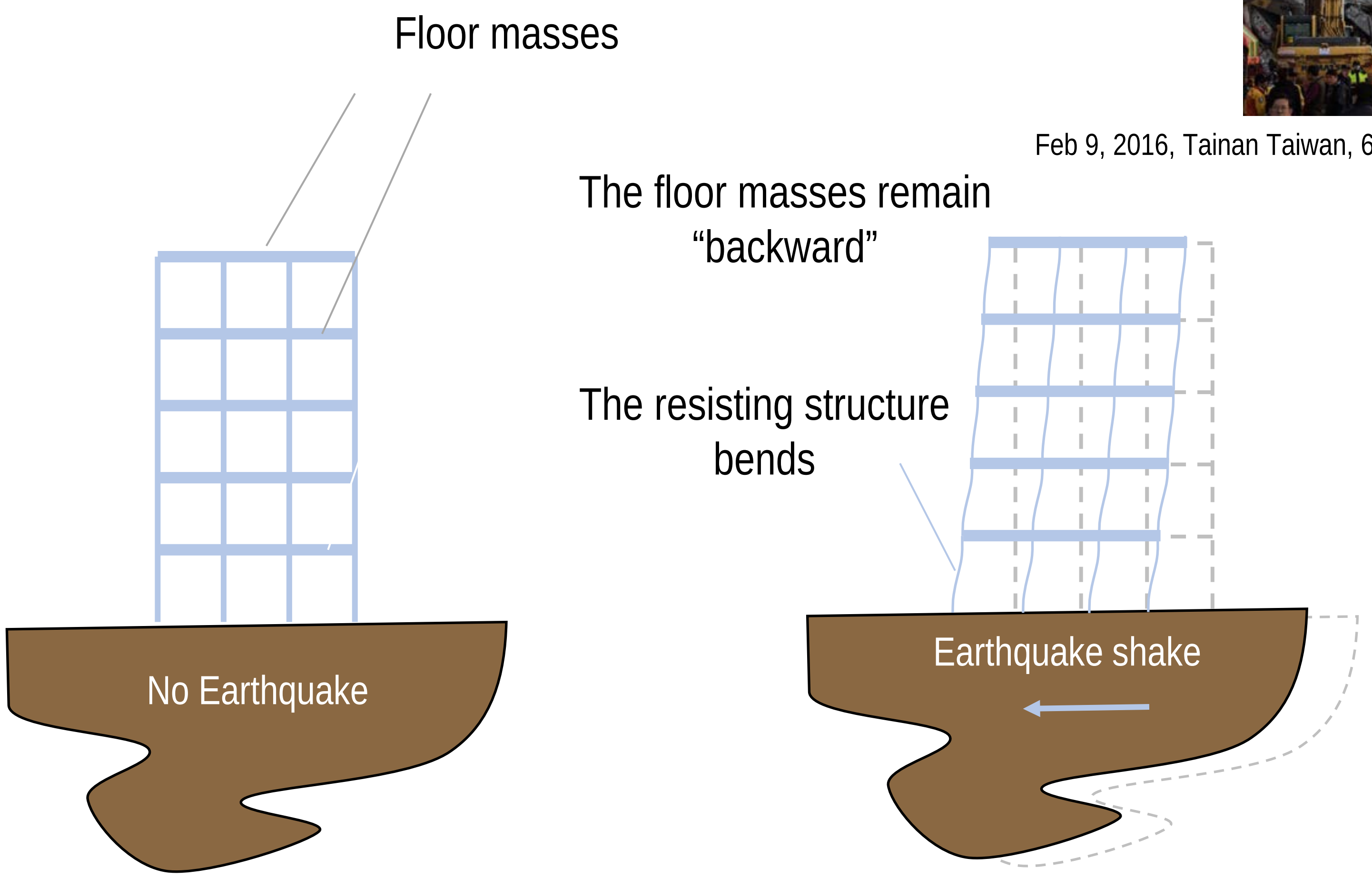
Response of a fixed-base building to an earthquake



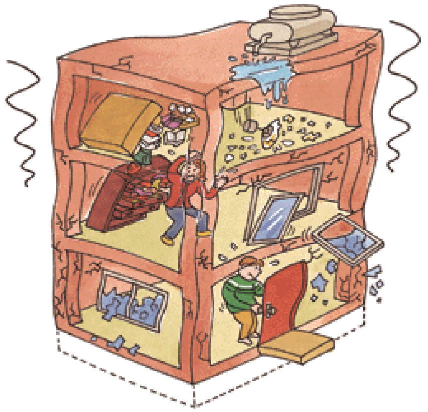
Feb 9, 2016, Tainan Taiwan, 6.4 M (*Anthony Wallace/Afp/Getty Images)*

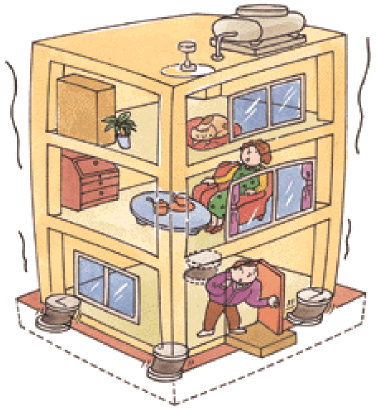


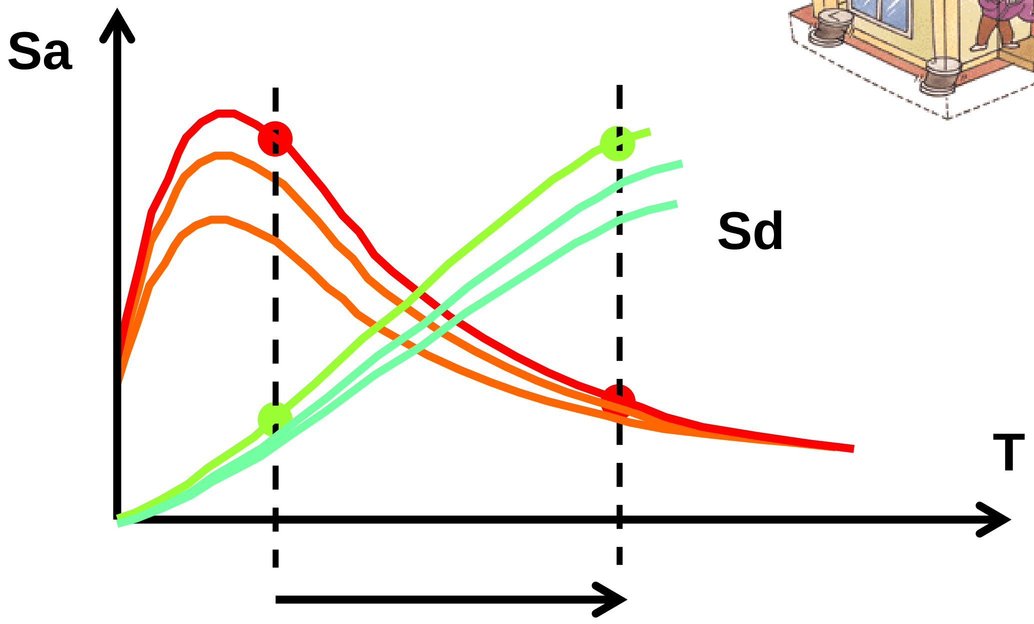
Neutral condition



Role of seismic isolation







Increase of the fundamental vibration period

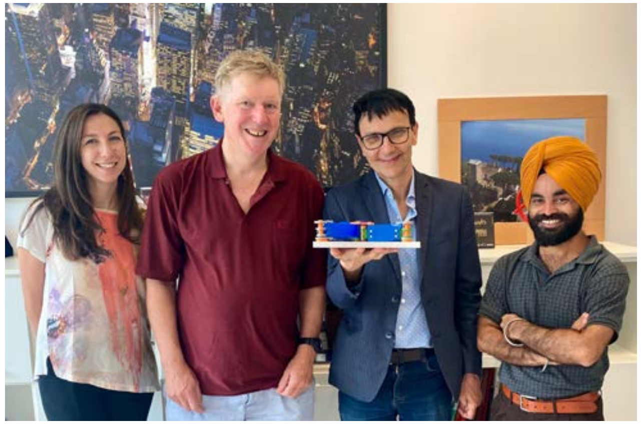
Limitations of currently available isolators

- confined operational frequencies
- manufacturing complexity
- need for advanced technical expertise
- significant weight
- substantial costs

These issues limit their use in developing countries essentially to relevant public buildings and infrastructures

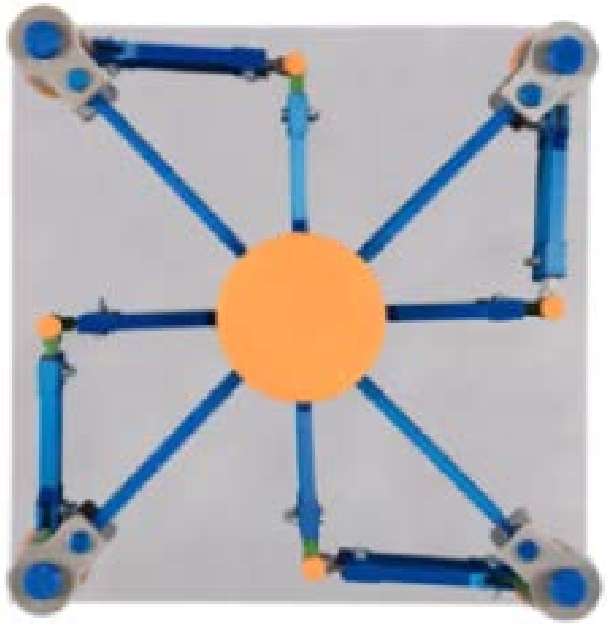
RESEARCH GOALS

- To trail-blaze a new path to seismic isolation.
- Design, modelling and experimental validation of a novel, biomimetic seismic isolator that mimics the mechanics of the human body
- Use of metallic parts and 3D-printed components, to avoid heavy industry or expensive materials
- Characterization of the tunability of the response of the proposed device
- Formulation of scaling laws of the experimental prototypes



Biomimetic design

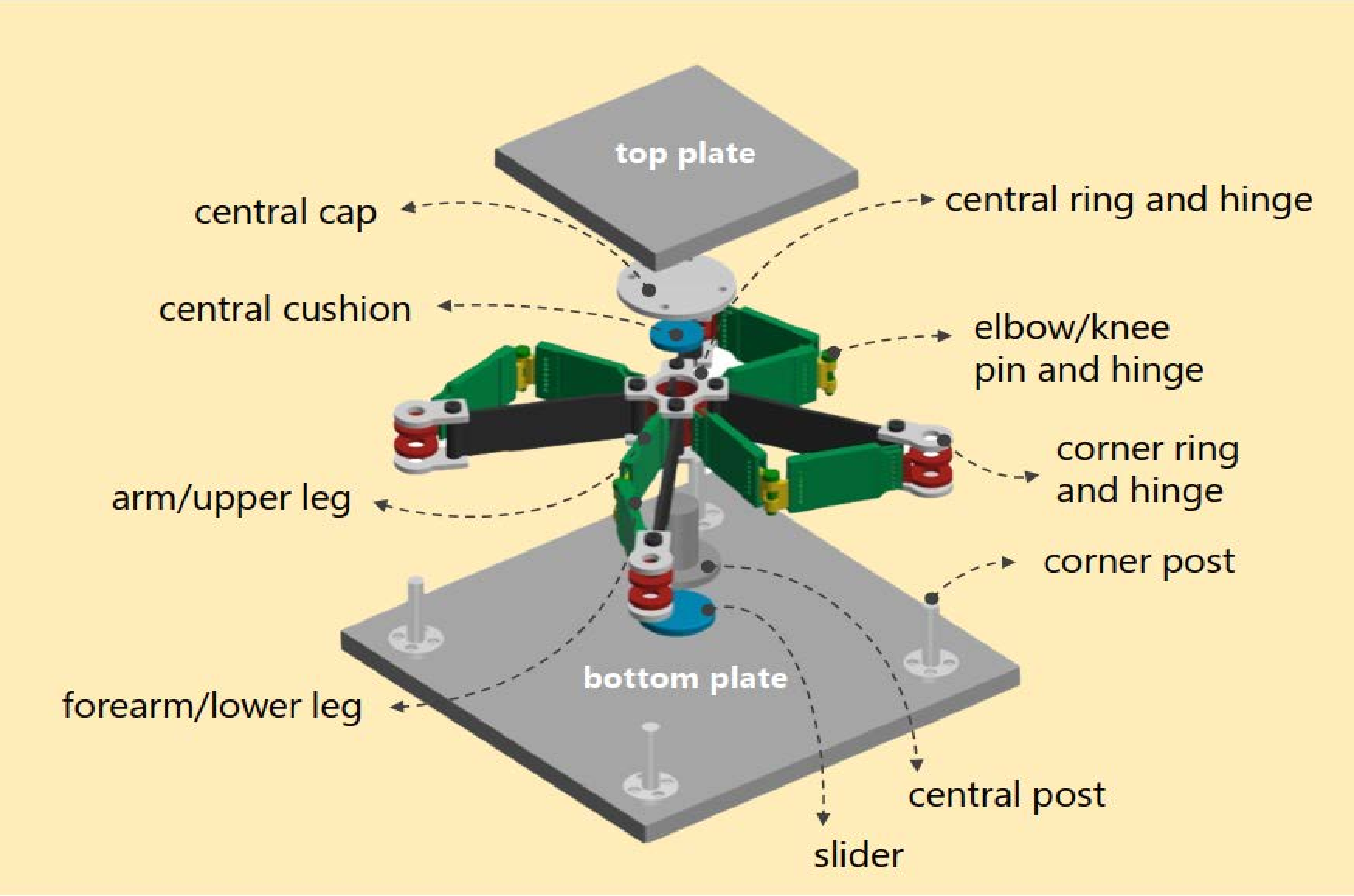
- Sliding-stretching seismic isolator (SSI)
- Unit cell composed of a central post that carries the vertical load and can slide against a base plate
- Four fixed corner posts are connected to the central post through stretchable “tendons” and rigid “limb” members
- The shape of the unit cell replicates that of a human body with bent arms and legs.



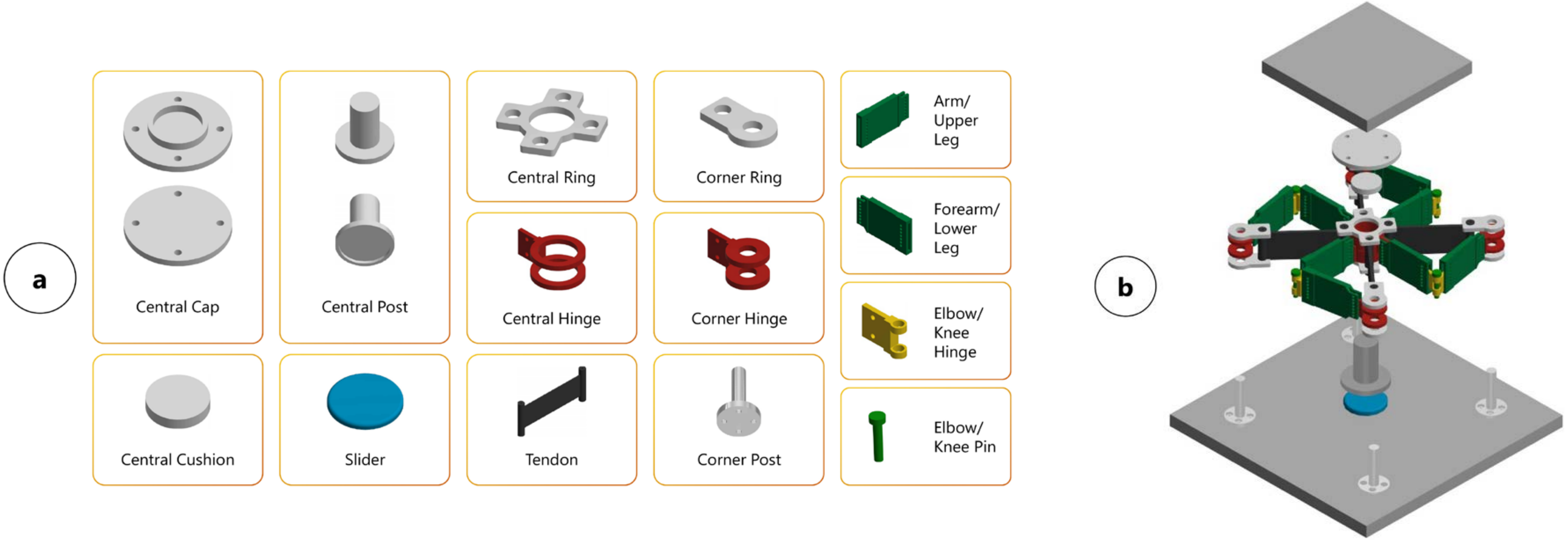
While animals move at resonance through the active control of locomotion by muscles and tendons, the SSI works in an opposite fashion: it tunes the nonlinear stiffness of the tendons so as to avoid resonance with the leading earthquake frequencies

MATERIALS AND METHODS

Unit cell design



Use of 3D printing techniques

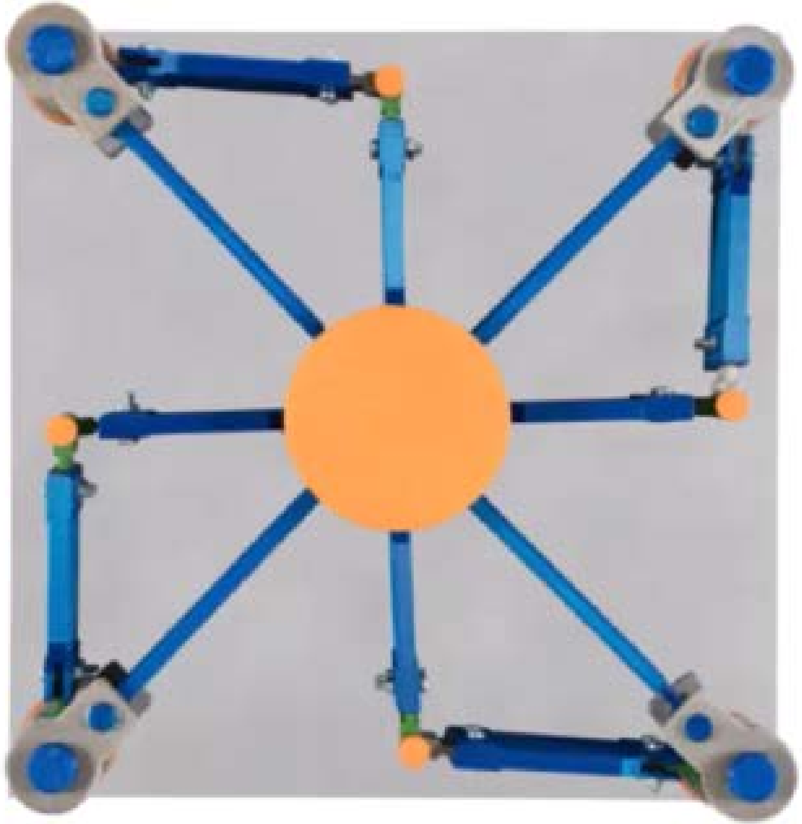


a) List of 3D-printable components; b) exploded view of the unit cell

Fabrication of physical models

A

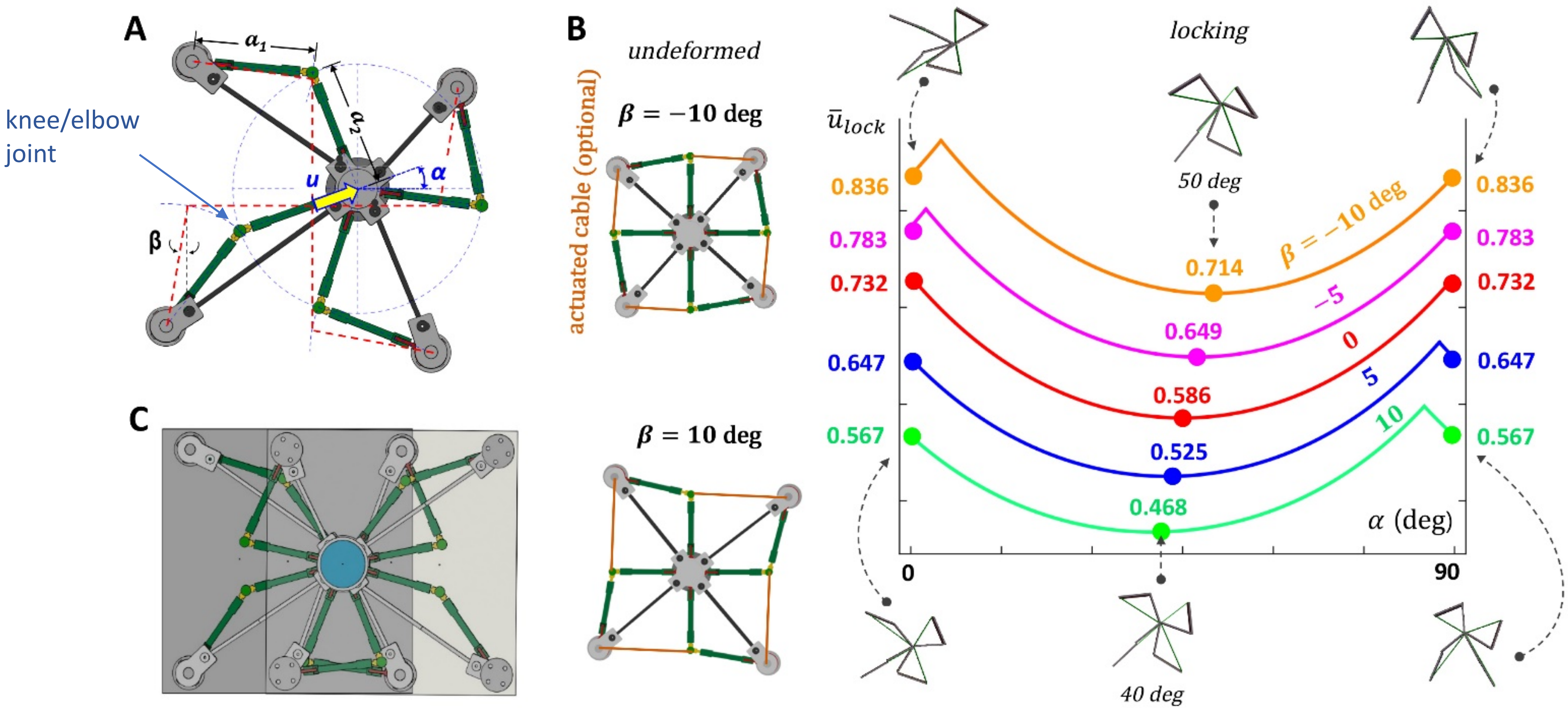
B



A: Demonstrative models without tendons. B: Demonstrative model with telescopic tendons

The fabricated SSI samples show lower limb length a_1=97.0 mm, upper limb length a_2=100.5 mm; and overall height equal to 95 mm (including the terminal plates). Top square plate 150-mm × 15-mm. Bottom square plate 250-mm × 15-mm.

Kinematics - 1



A: Kinematics of the unit cell.

B: Locking displacements versus loading angle alpha and rest angle beta.

C: Deformed configuration of a two-layer system

Kinematics-2

Lower displacement capacity

Motion animation for beta=+10deg

Greater displacement capacity

Motion animation for beta=-10deg

Experimental validation procedure

Cycling test on a prototype without tendons

Cycling test on a prototype with tendons

Experimental validation procedure

Experimental setup: loading frame equipped with a 500 kN vertical hydraulic actuator (100-mm stroke), a 100-kN horizontal hydraulic actuator (stroke 100 mm, actuation frequency up to 8 Hz)

MECHANICAL MODELING – Pseudo-elastic response of tendons

The restoring force of the tendons (F_r) is well described by a pseudo-elastic (PE) constitutive model:

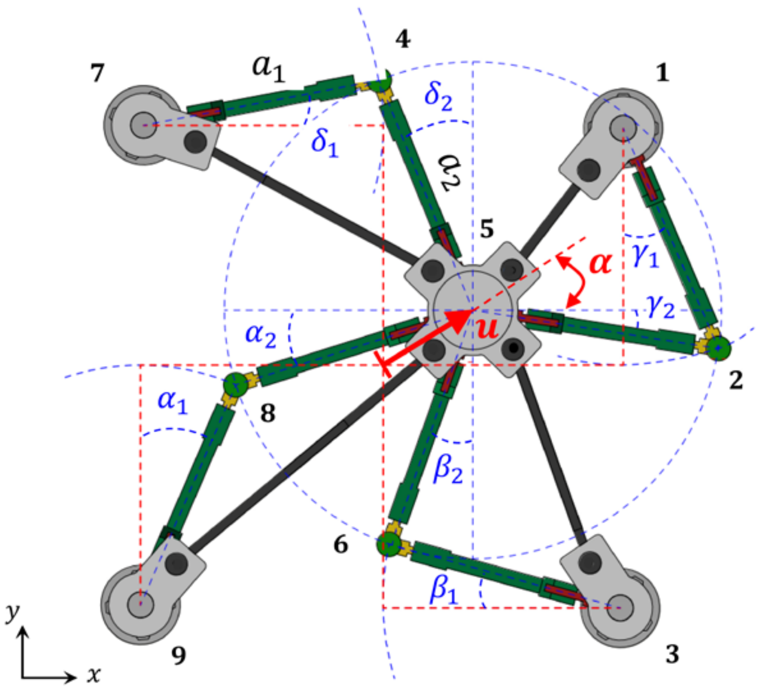
λ = Stretch ratio (after pre-conditioning)

$\hat{\sigma}_t$ = Nominal stress carried by the tendons

A_t = Cross-section area

ψ = Strain-rate factor

$\hat{\mathbf{k}}_{t,j}$ = unit vector in the direction of tendon j-5



$$F_r = A_t \left(\sum_j (1+\psi)\, \hat{\sigma}_t(\lambda_{t,j})\, \hat{\mathbf{k}}_{t,j} \right) \cdot \hat{\mathbf{k}}^u$$

Hysteretic response of the tendons

Different response during loading and unloading:

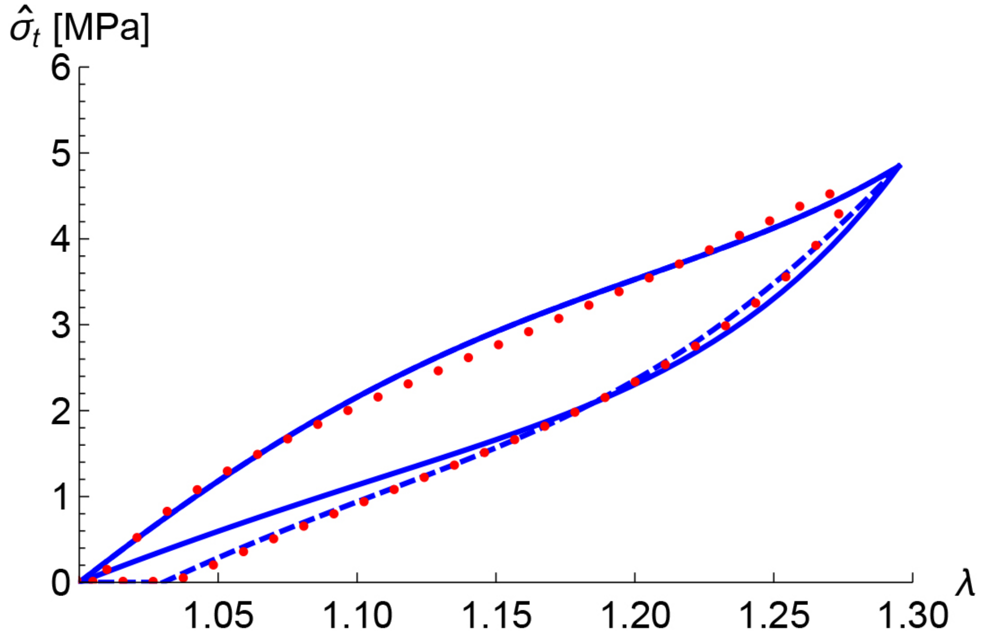
$\hat{\sigma}_t^{(l)}$ and $\hat{\sigma}_t^{(u)}$ respectively denote the nominal stress on the loading path and the unloading path

$W(\lambda)$ denotes the expression of the strain energy function accounting for the incompressibility constraint

$\eta, \eta_2, \nu_1, \nu_2$ are softening (damage) parameters

$$\hat{\sigma}_t^{(l)} = \frac{dW(\lambda)}{d\lambda}$$

$$\hat{\sigma}_t^{(u)} = \eta\hat{\sigma}_t^{(l)} + (1-\eta_2)(v_1\lambda - v_2\,\lambda^{-2})$$

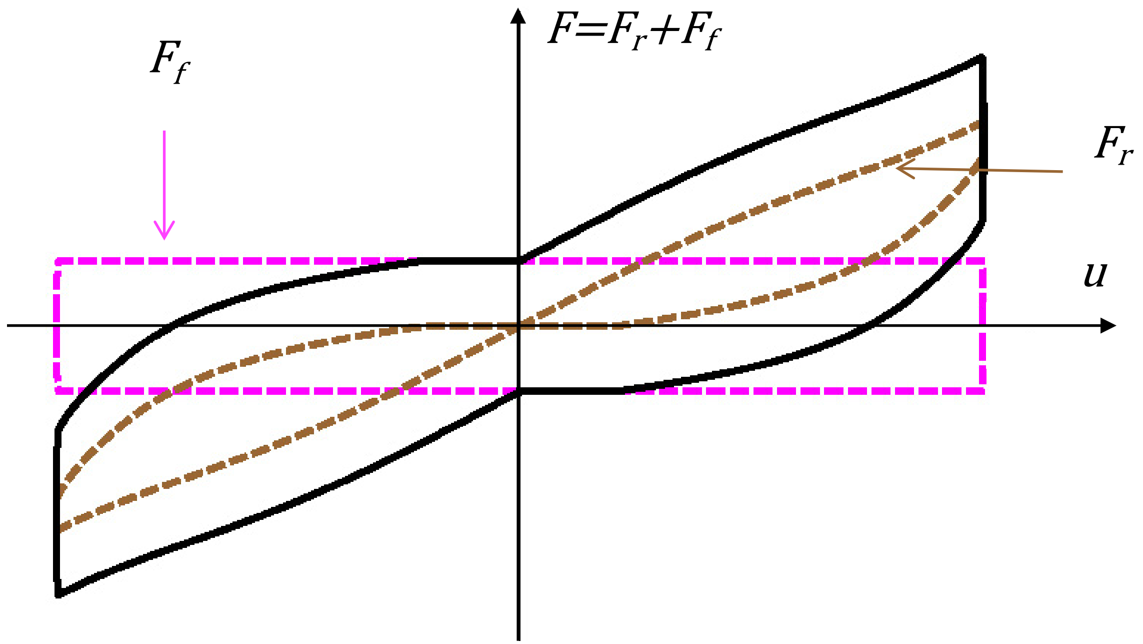


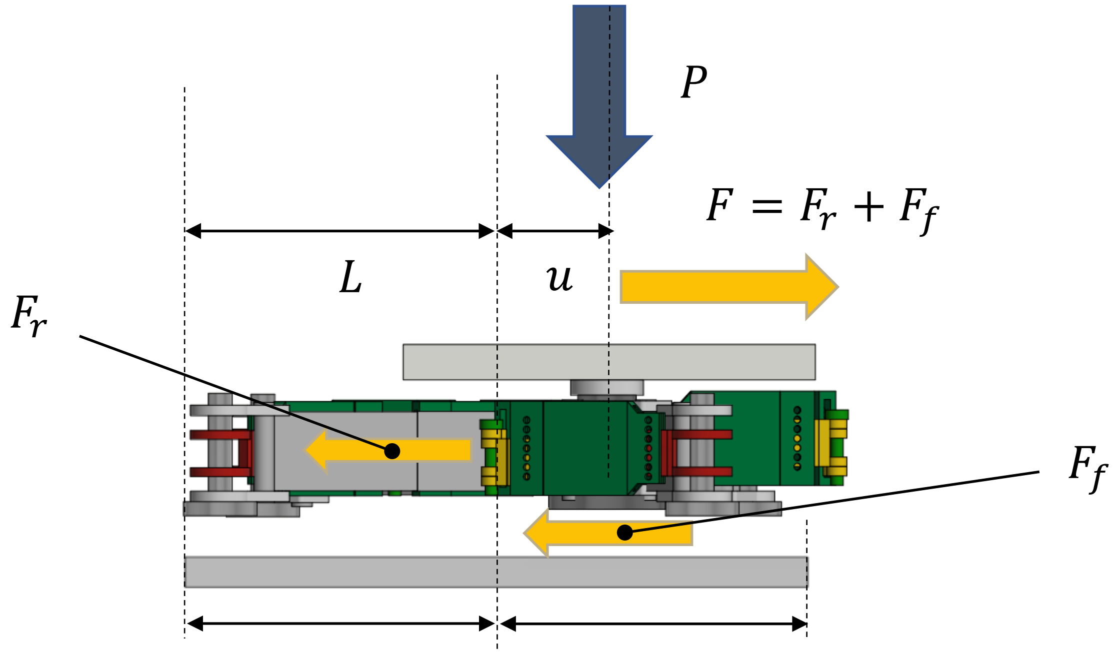
Overall mechanical modeling

Friction force at the base of the central post

$$F_f = \mu\, P\, sign(v)$$

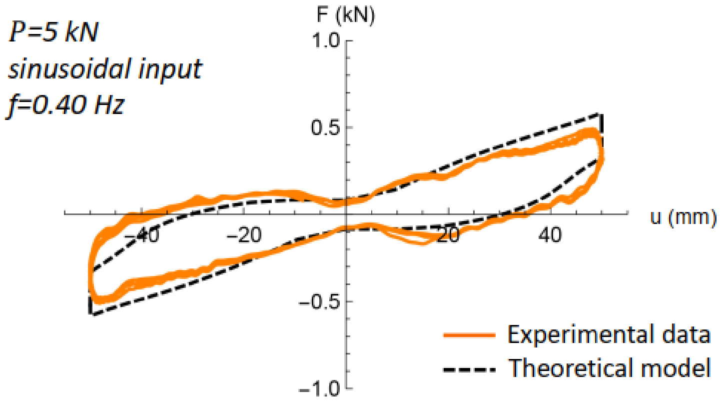
where μ is a friction coefficient that depends in a nonlinear fashion on the current values of the vertical load P and the sliding velocity v

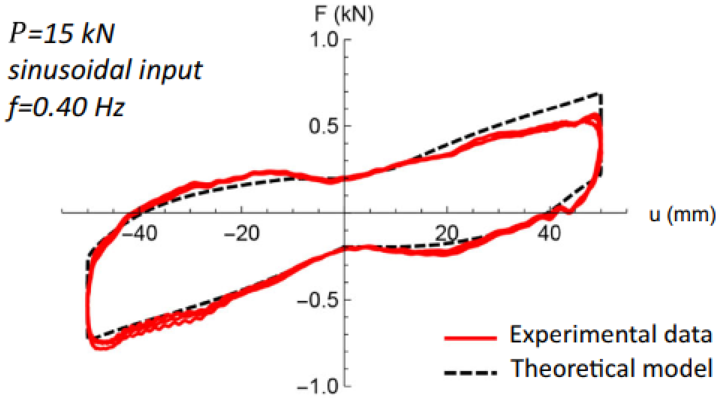


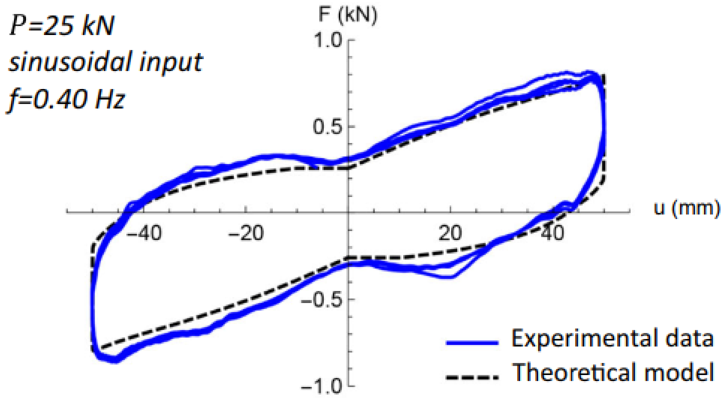


Components of the overall lateral force-lateral displacement response

RESULTS AND DISCUSSION –
Experimental response of prototype #2 (with tendons)







Comparison of experimental results and theoretical predictions under fixed vertical load P and cyclic displacement histories with amplitude $d = \pm 50$ mm, for $P = 5, 15, 25$ kN (prototype # 2)

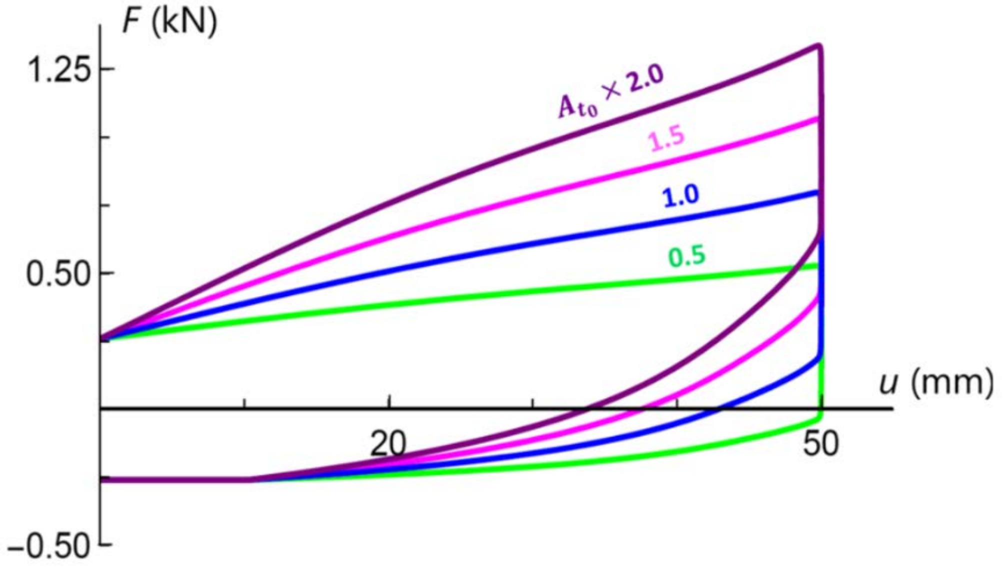
Summary of the main results of the experimental validation tests

Prototype #1: effective (average) friction coefficient μ_{eff} varying from 1.66% (*P*= 5 kN) to 1.04% (*P* = 25 kN)

Prototype #2: effective damping coefficient ξ_{eff} = 17.05%, 24.72%, 27.84% for *P* = 5, 15 kN and 25 kN, respectively

Effective vibration period T_{eff} = 1.32 s, 2.09 s, and 2.51 s for *P* = 5, 15 kN and 25 kN, respectively

Force-displacement responses of prototype #2 for variable sizes of the tendons



SCALING LAWS

- The results of prototype tests can be generalized to SSIs of different sizes and load-displacement capacities.
- A load carrying capacity of 250 kN, e.g., requires the adoption of a central post with a 41-mm diameter, and a PTFE slider with a 95-mm diameter,
- For what concerns the displacement capacity, it is possible to reach d=500 mm using a 1-layer system with limbs' length a=710 mm, or a 2-layer system with a=355 mm.
- Scaling law of the tendons: $F_{r_d}(P) = \chi P$

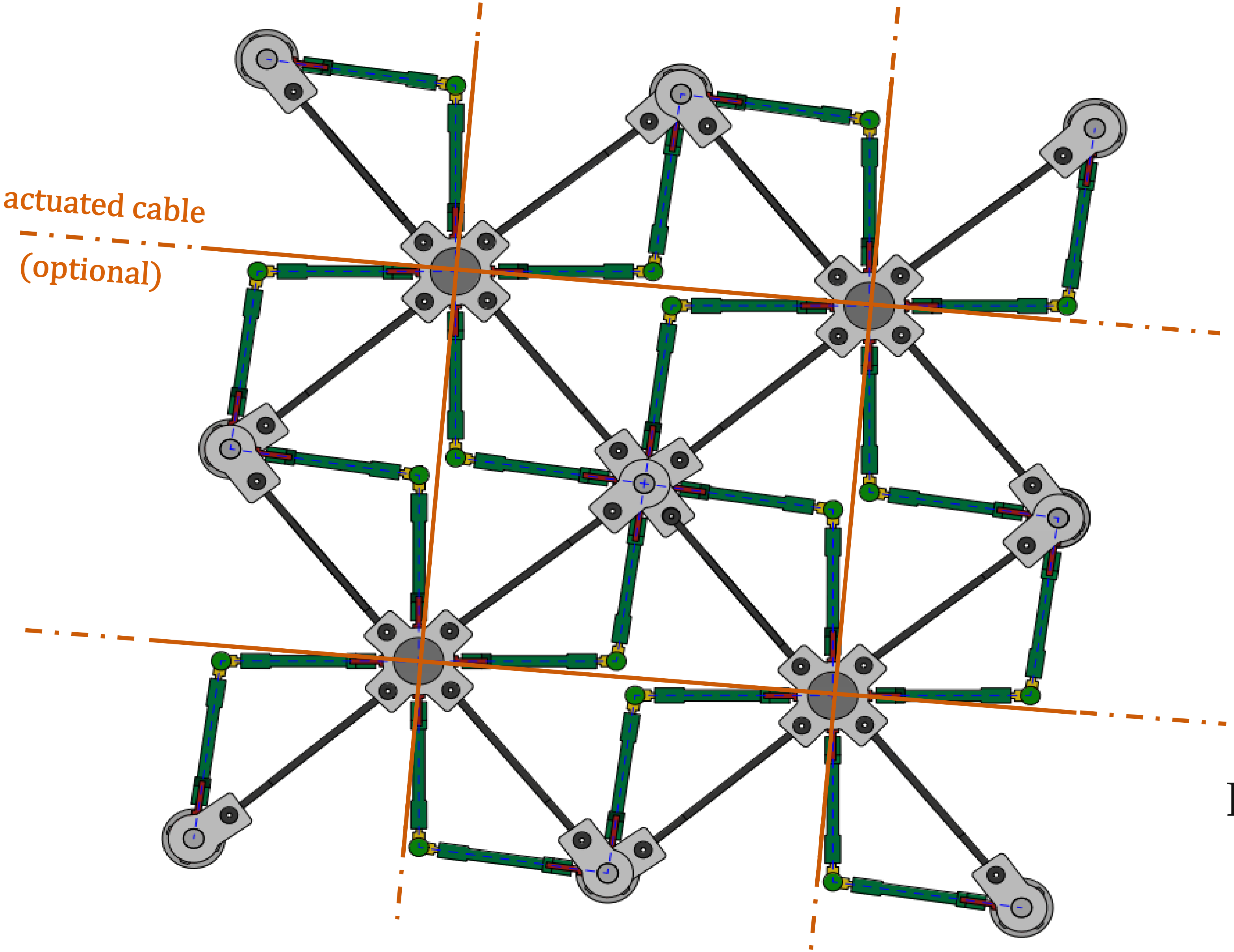
where F_{r_d} indicates the design value of tendons' restoring force, and χ denotes a dimensionless parameter(*)

(*) See, e.g., AASHTO: Guide Specifications for Seismic Isolation Design-Interim 2000. American Association of State Highways and Transportation, 2000)

CONCLUDING REMARKS - 1

- The rescaling of the prototype tests lead us conclude that the design variables T_{eff} and ξ_{eff} depend on the geometry of the device, the current value of μ_{eff}, the ratio χ between the design value of the recentering force of the tendons and the maximum vertical load, and a dimensionless parameter λ characterizing the energy dissipation capacity of the tendons
- The friction coefficient can be tuned by playing with the vertical load and the size and materials of the slider and the resting plate
- The tendons' energy dissipation properties can be adjusted through their preliminary training, in addition to an optimized design of the geometry and materials.

CONCLUDING REMARKS - 2



Periodic metaisolators