Department of Civil Engineering
PhD Course on Risk and Sustainability in Civil, Architectural and Environmental Engineering Systems

University of Salerno, Department of Civil Engineering

PhD Course in Risk and Sustainability in Civil Engineering, Architecture, Environmental Engineering Systems

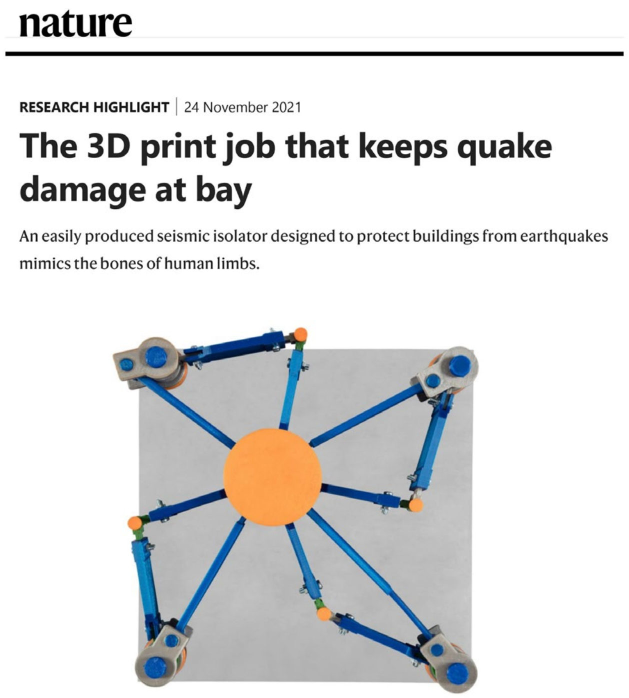
DESIGN, MECHANICAL MODELLING AND TESTING OF INNOVATIVE SEISMIC ISOLATION DEVICES

Academic Year: 2021/2022
PhD Coordinator: Prof. Fernando Fraternali

PhD Student: Narinder Singh
Supervisor: Prof. Ada Amendola
Co-supervisor: Prof. Fernando Fraternali

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

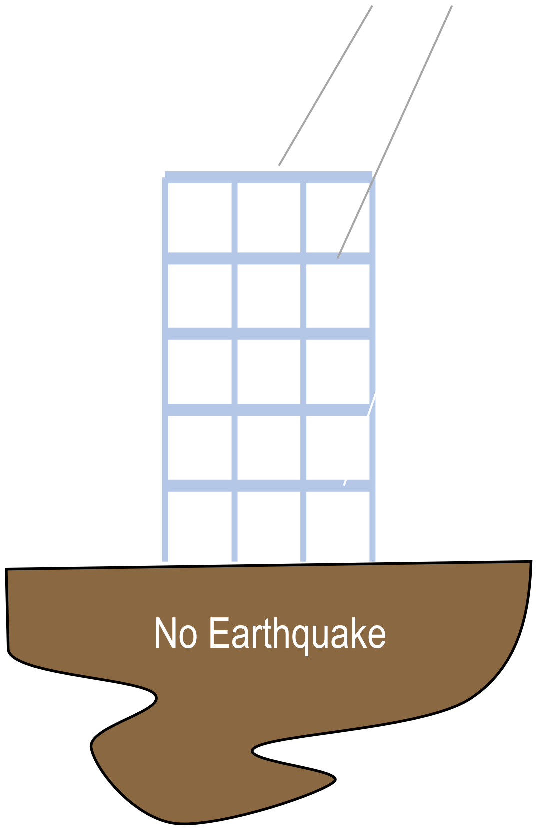
An easily produced seismic isolator designed to protect buildings from earthquakes mimics the bones of human limbs.

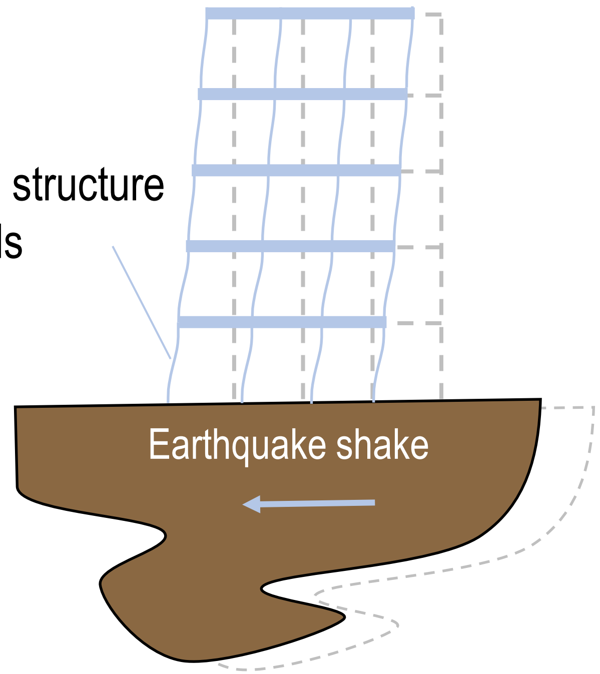
Main publications:
- Fraternali, F., **Singh, N.,** Amendola, A., Benzoni, G., Milton, G.W. A biomimetic sliding–stretching approach to seismic isolation. NONLINEAR DYNAMICS, 106(4), 3147-3159, 2021
- Fraternali, F., **Singh, N.,** Amendola, A., Benzoni, G., Milton, G.W. The 3D print job that keeps quake 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

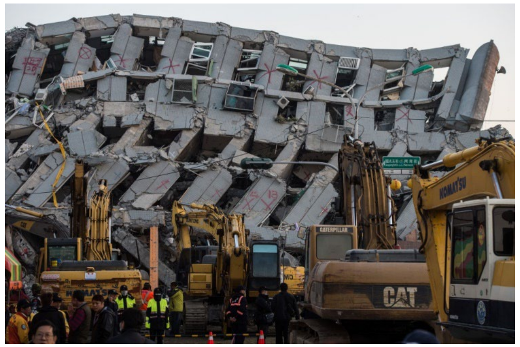
INTRODUCTION

Response of a fixed-base building to an earthquake

Neutral condition

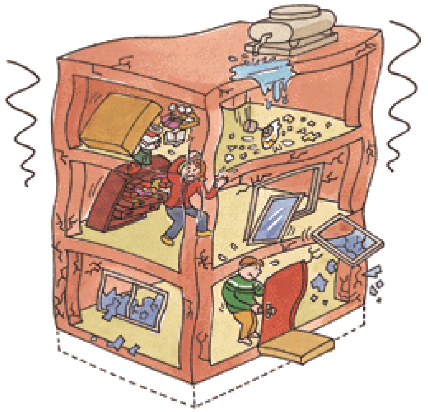


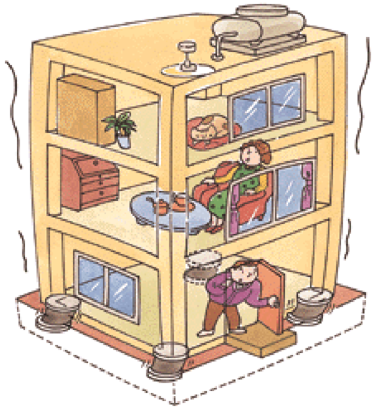


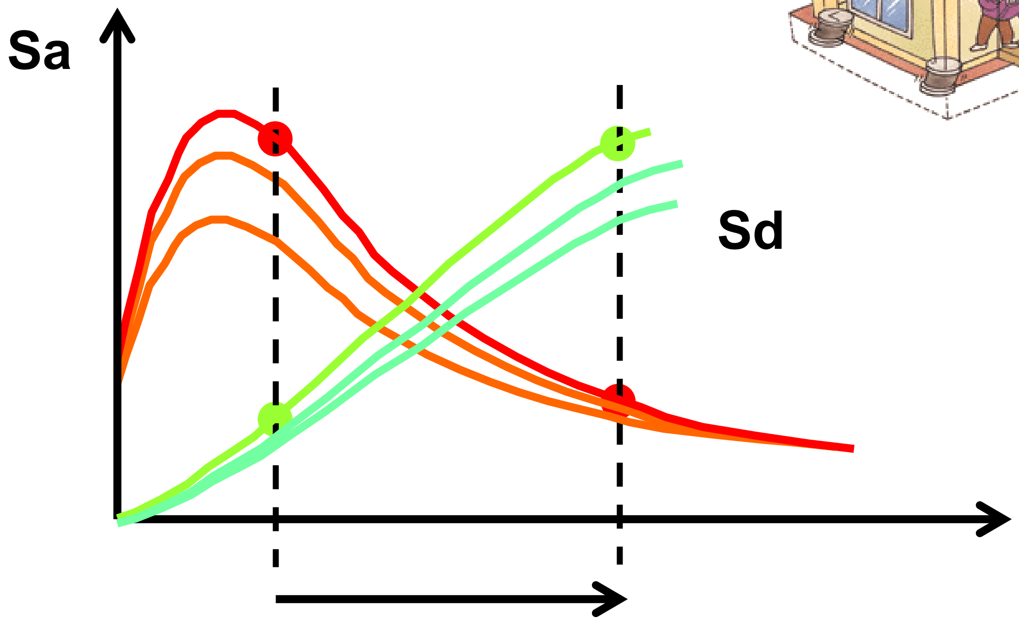


Feb 9, 2016, Tainan Taiwan, 6.4 M ***(Anthony Wallace/Afp/Getty Images)***

Role of seismic isolation

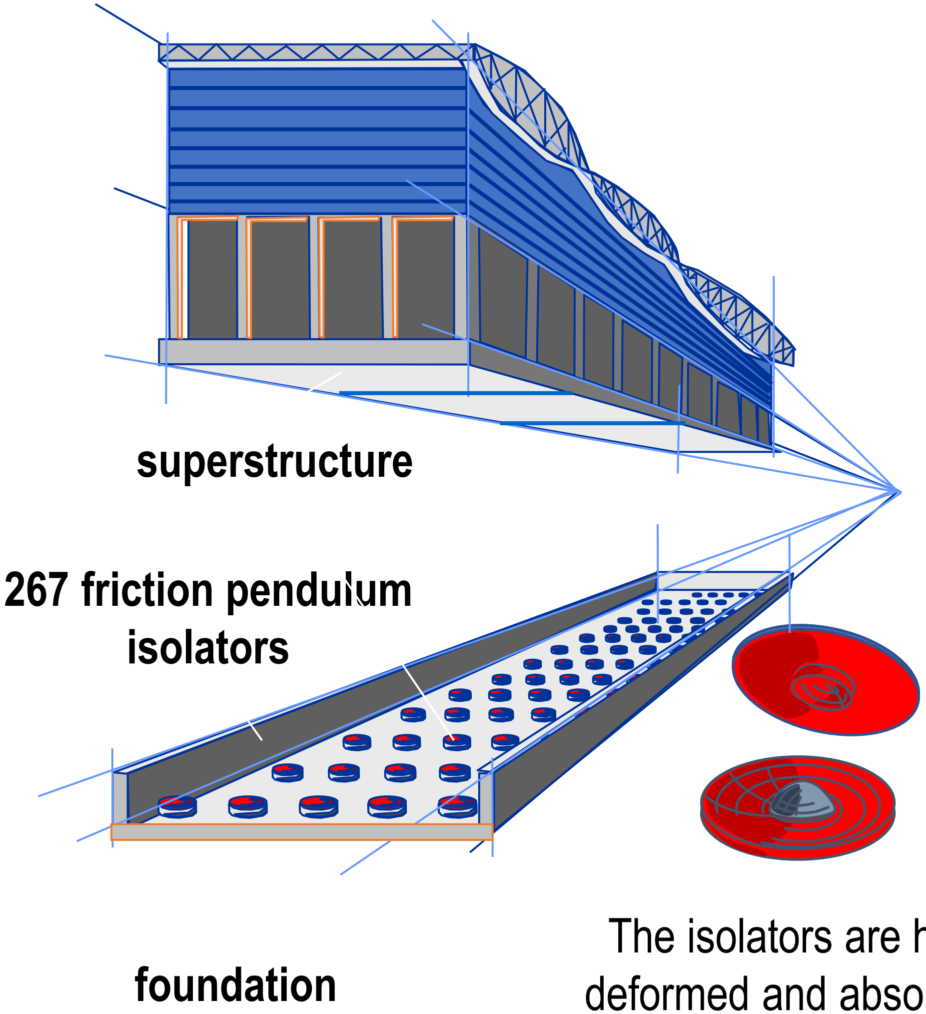




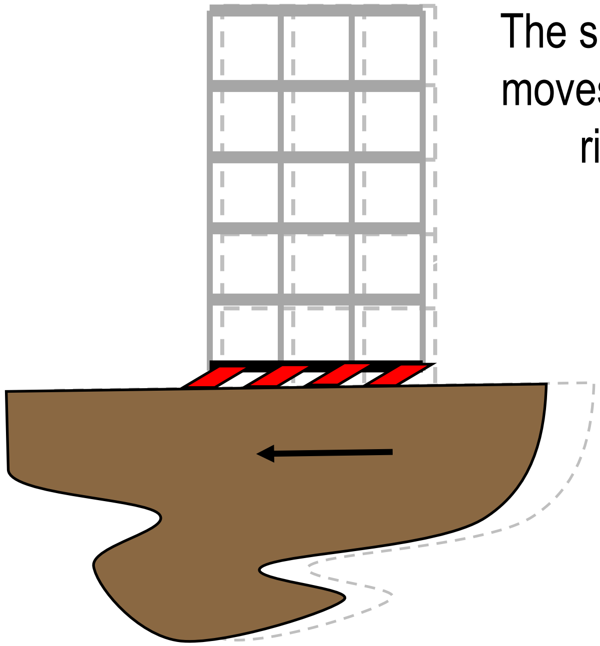


Increase of the fundamental vibration period

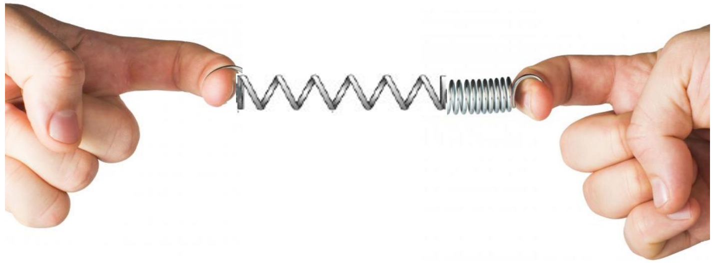
Example of a modern isolated structure: San Francisco Flight Terminal



The isolators are heavily deformed and absorb large part of the input energy



The superstructure moves almost as a rigid body

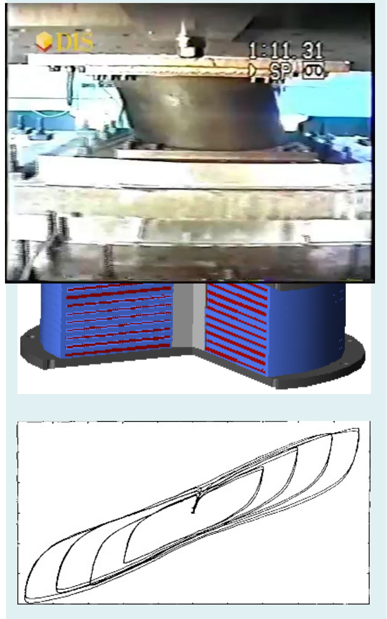


Homemade isolation techniques in rural houses of Lahijan (Iran)

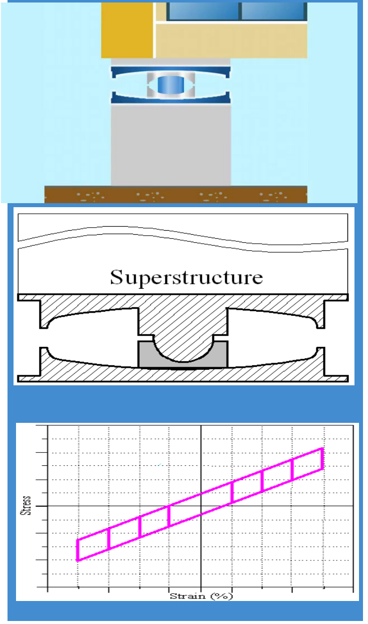
Modern seismic protection devices currently available on the market

seismic isolators

Elastomeric

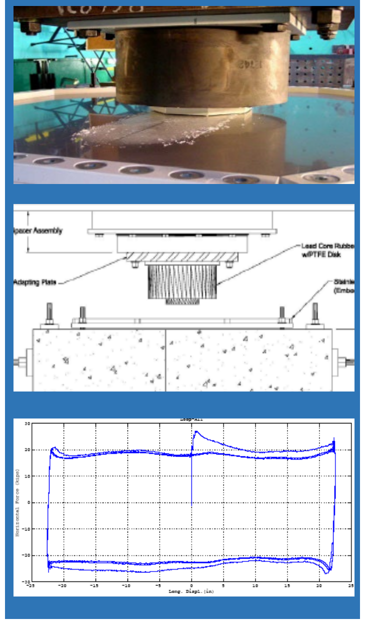


Friction-type

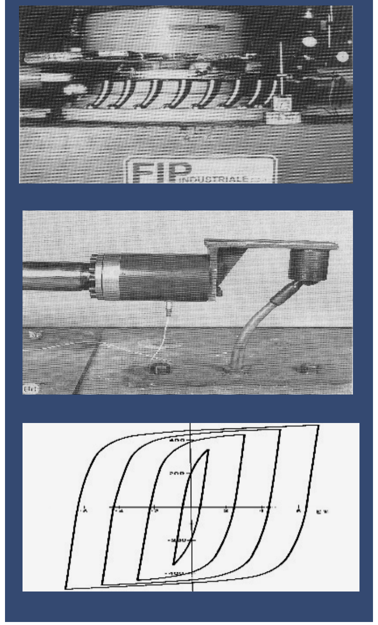


energy dissipation devices

Hybrid



Yielding



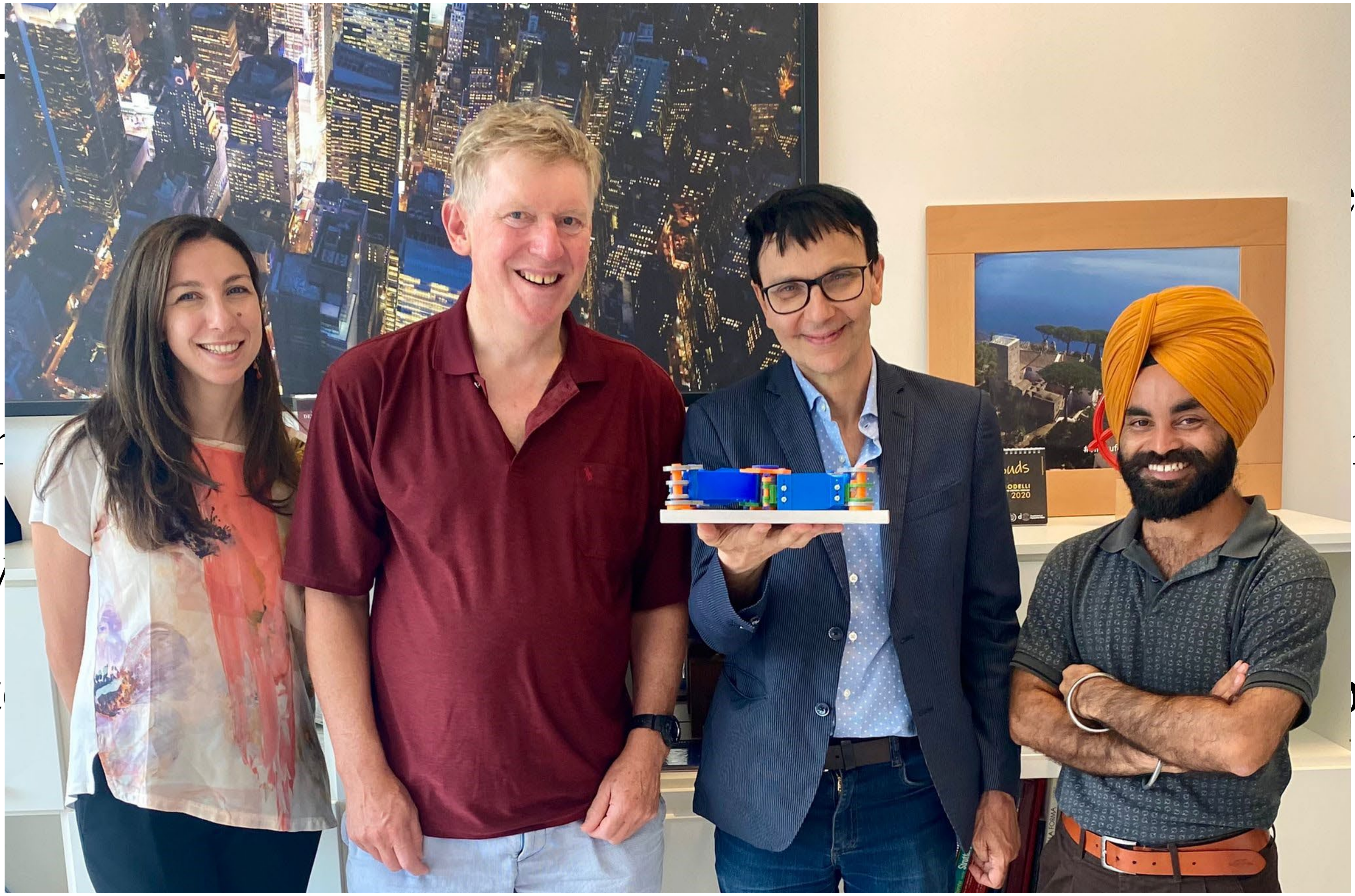
Limitations of currently available isolators

- 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

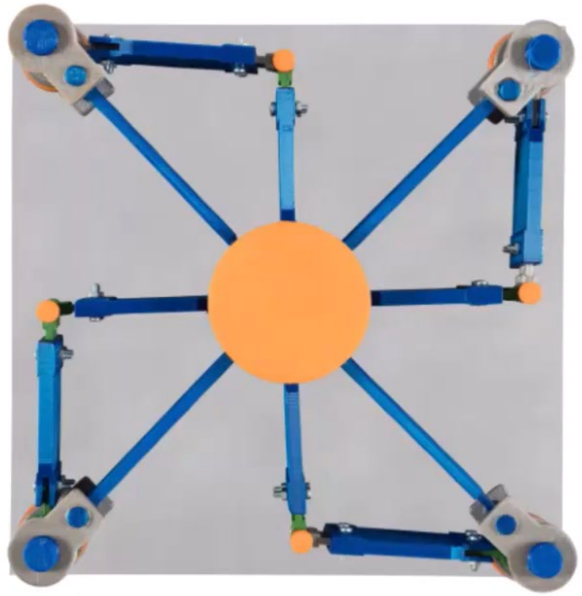
- To trail-
- Design, … l, biomimetic
  seismic … body
- Use of r … id heavy
  industry
- Charact … proposed
  device



- Formulation of scaling laws of the experimental prototypes

Biomimetic design

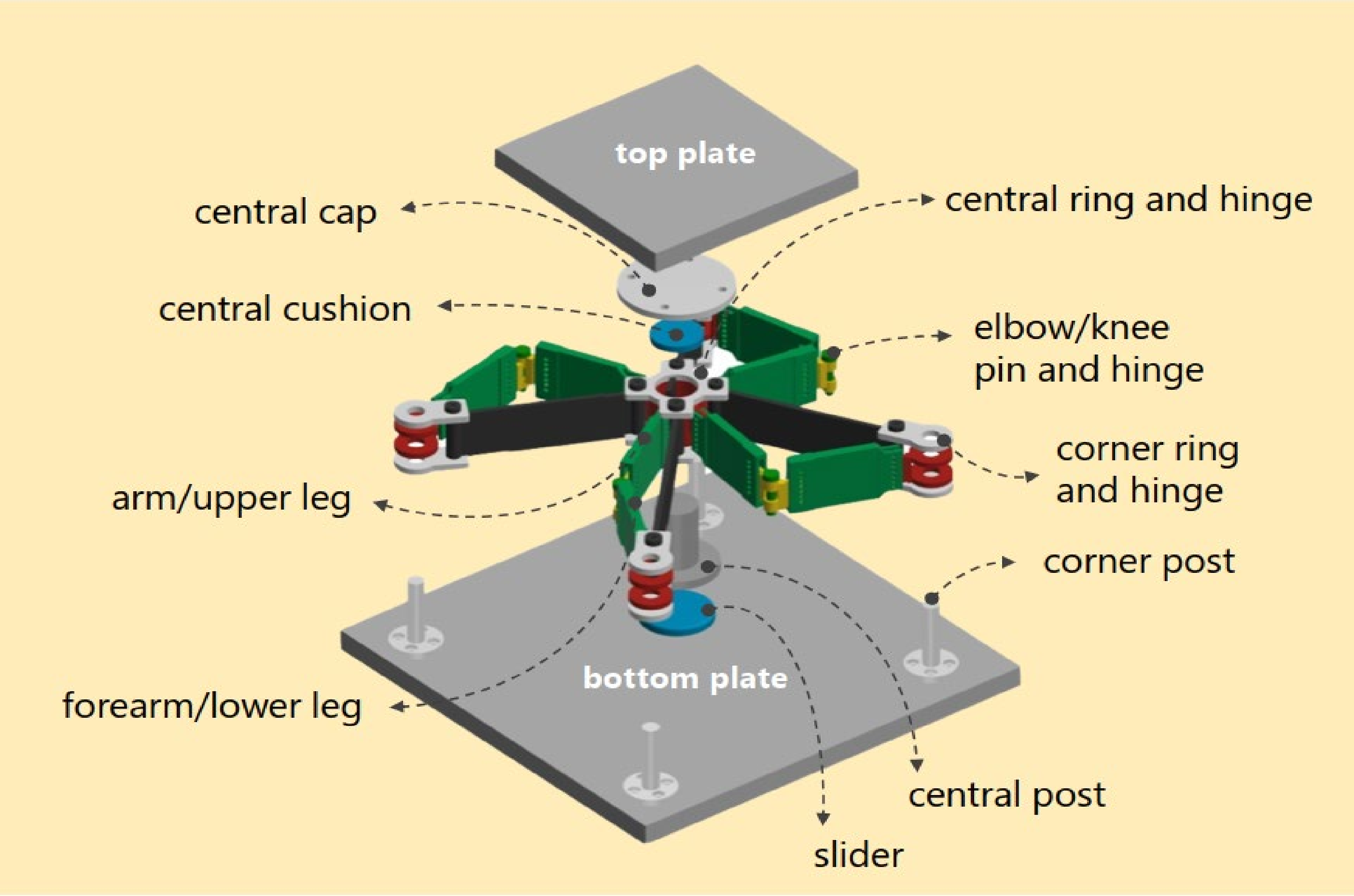
- Sliding-stretching seismic isolator (SSI)
- Unit cell composed of a central post that carries the vertical load and can slide against a base plate
- Four fixed corner posts are connected to the central post through stretchable “tendons” and rigid “limb” members
- The shape of the unit cell replicates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



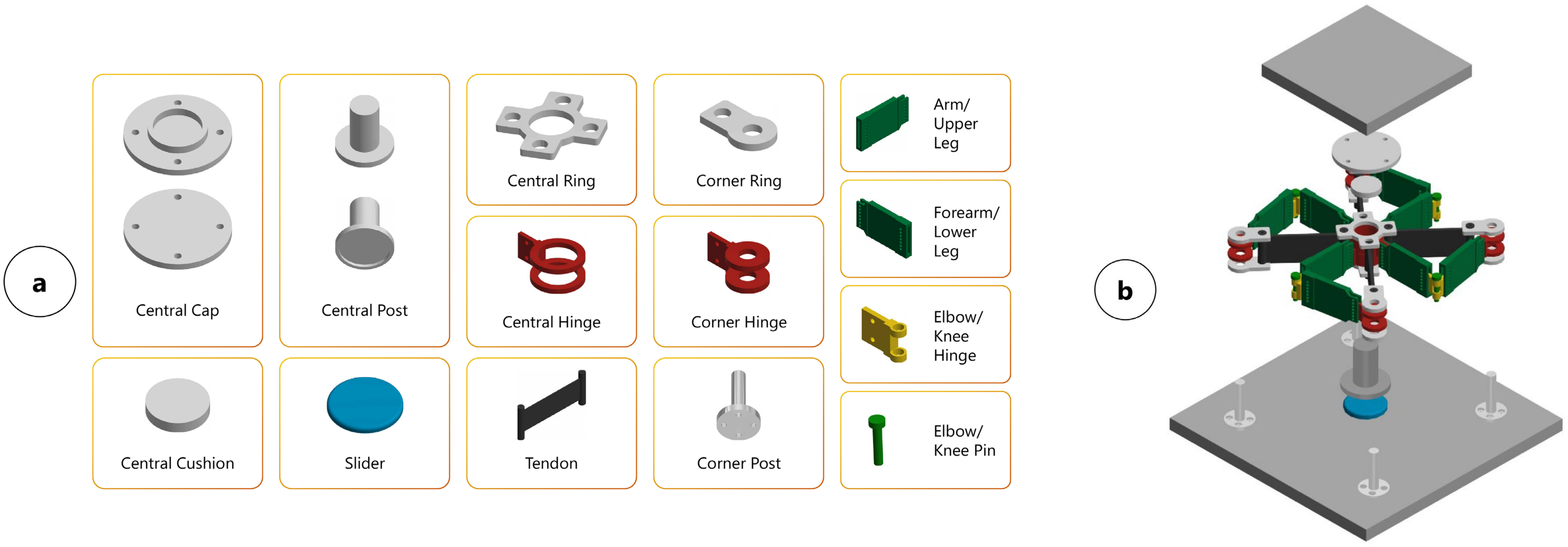
While animals move at resonance through the active control of locomotion by muscles and tendons, the SSI works in an opposite fashion: it tunes the nonlinear stiffness of the tendons so as to avoid resonance with the leading earthquake frequencies

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

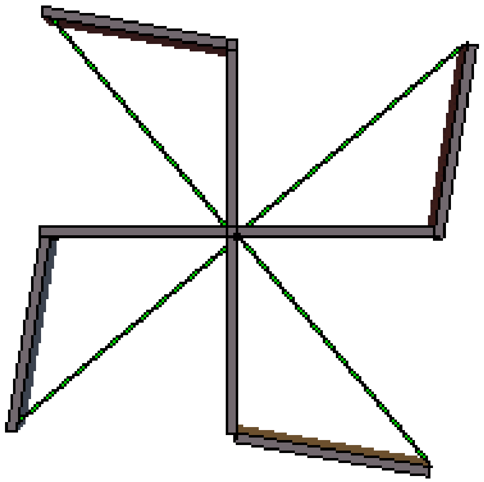
A B

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.

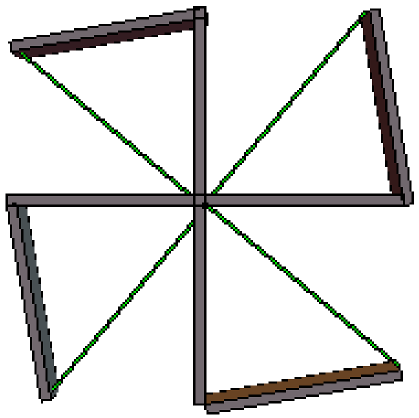
Kinematics

Lower displacement capacity



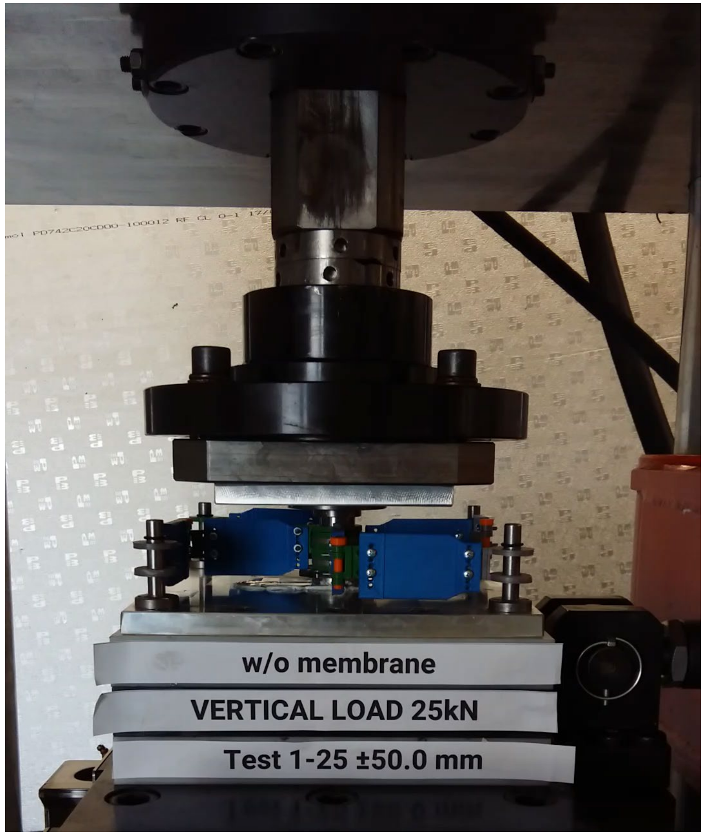
a) Motion animation for beta = +10 deg

Greater displacement capacity



b) Motion animation for beta = -10 deg

Experimental validation procedure



Cycling test on a prototype without tendons

Cycling test on a prototype with tendons

1 training cycle and 4 additional cycles of a sinusoidal displacement time-history with a frequency of 0.40 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:

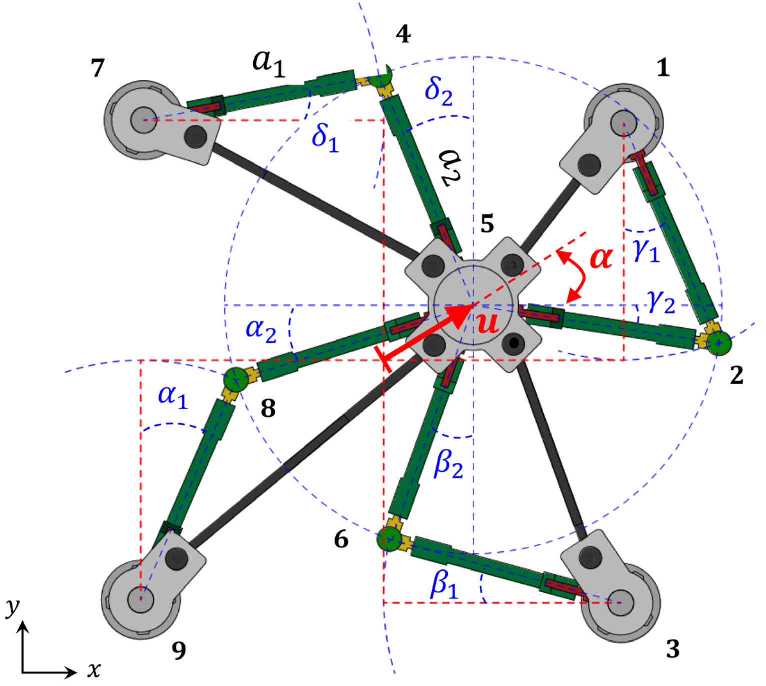
$\lambda =$ Stretch ratio (after pre-conditioning)

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

$A_t =$ Cross-section area

$\psi =$ 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:

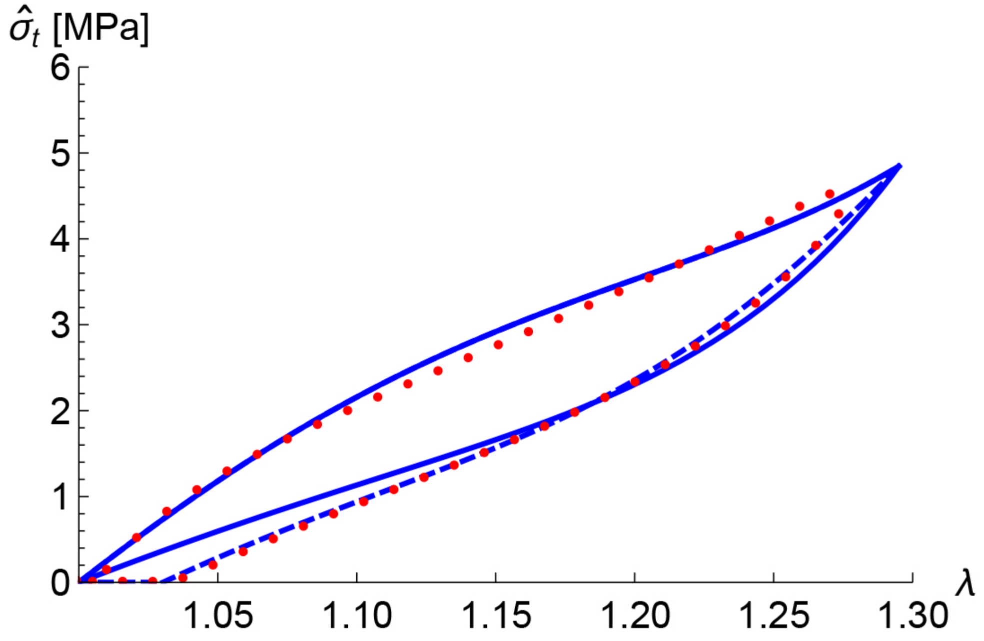
$\hat{\sigma}_t^{(l)}$ and $\hat{\sigma}_t^{(u)}$ respectively denote the nominal stress on the loading path and the unloading path

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

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

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

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

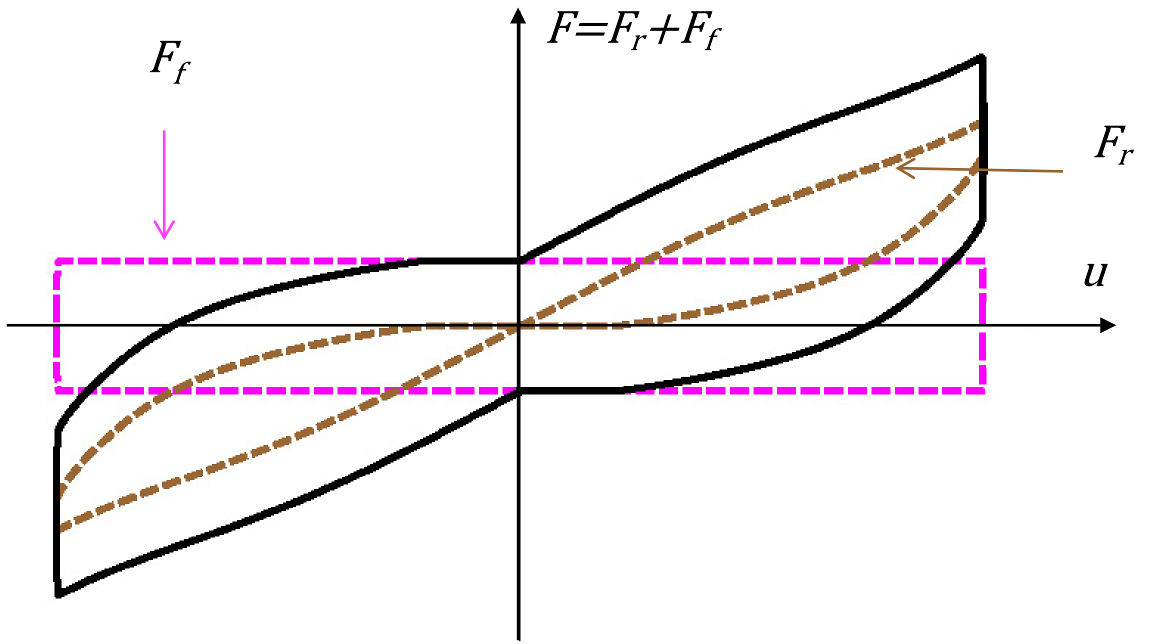


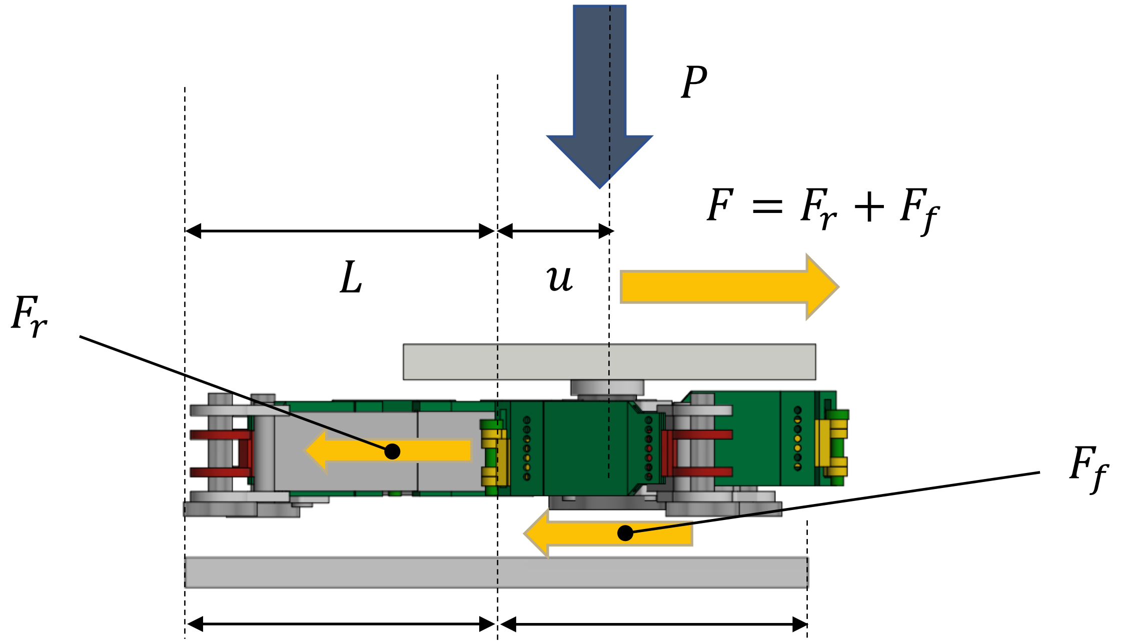
Overall mechanical modeling

Friction force at the base of the central post

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

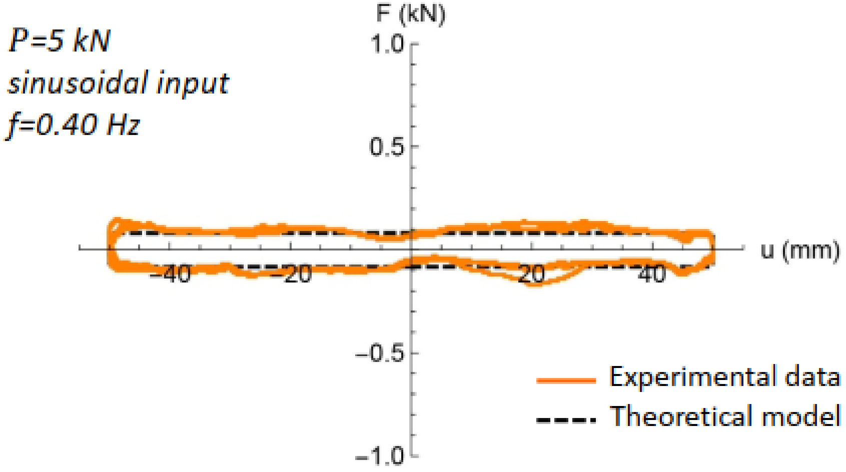
where μ is a friction coefficient that depends in a nonlinear fashion on the current values of the vertical load P and the sliding velocity v

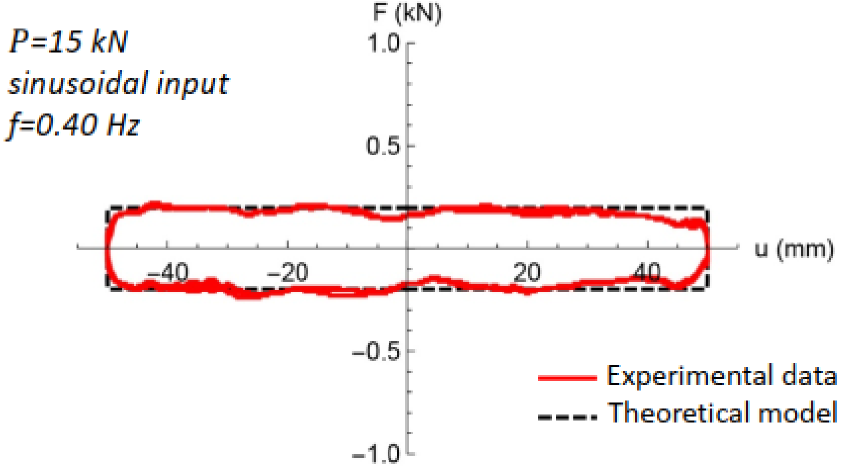


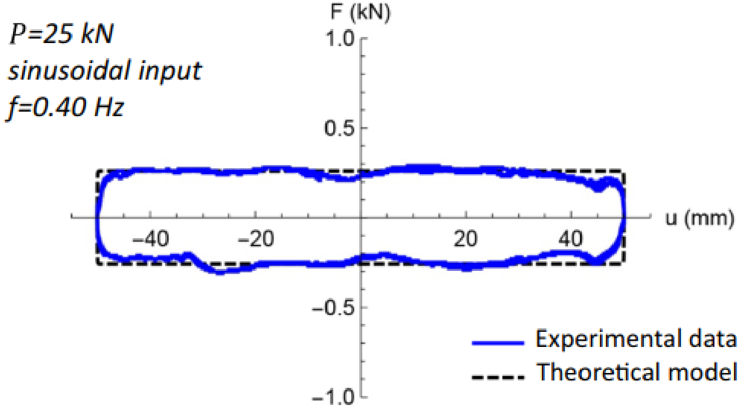


Components of the overall lateral force-lateral displacement response

RESULTS AND DISCUSSION –
Experimental response of prototype #1 (without tendons)

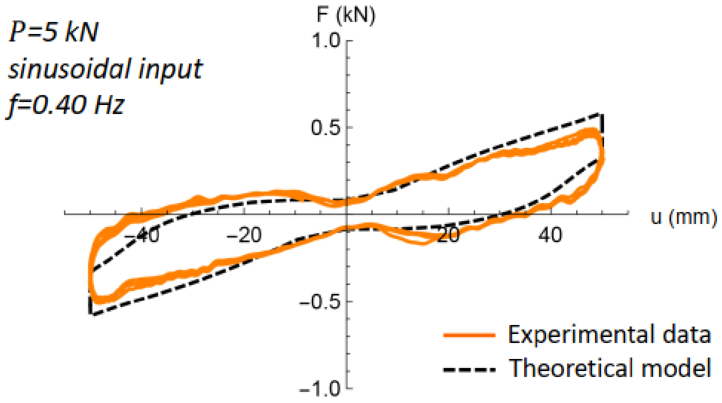


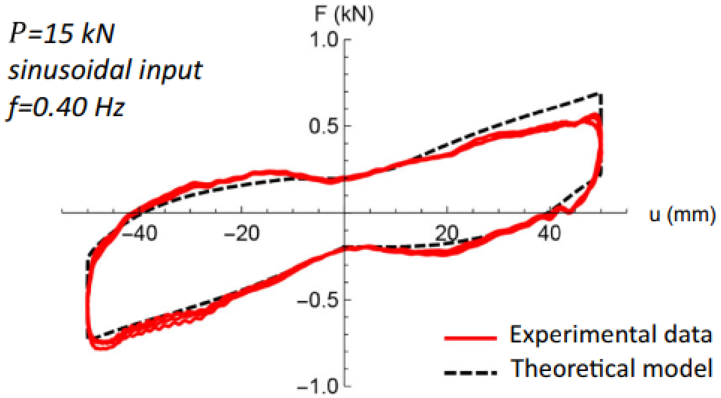


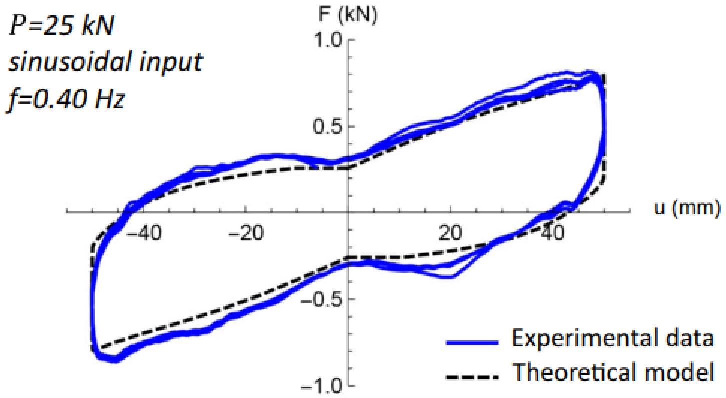


Comparison of experimental results and theoretical predictions under fixed vertical load P and cyclic displacement histories with amplitude d = ±50 mm, for P = 5, 15, 25 kN (prototype #1)

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)

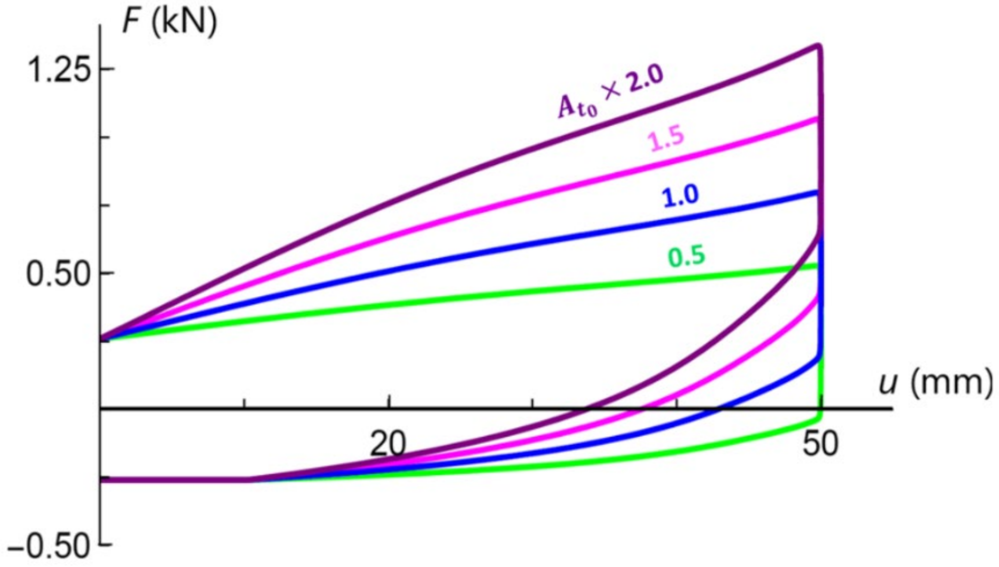
Summary of the main results of the experimental validation tests

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)

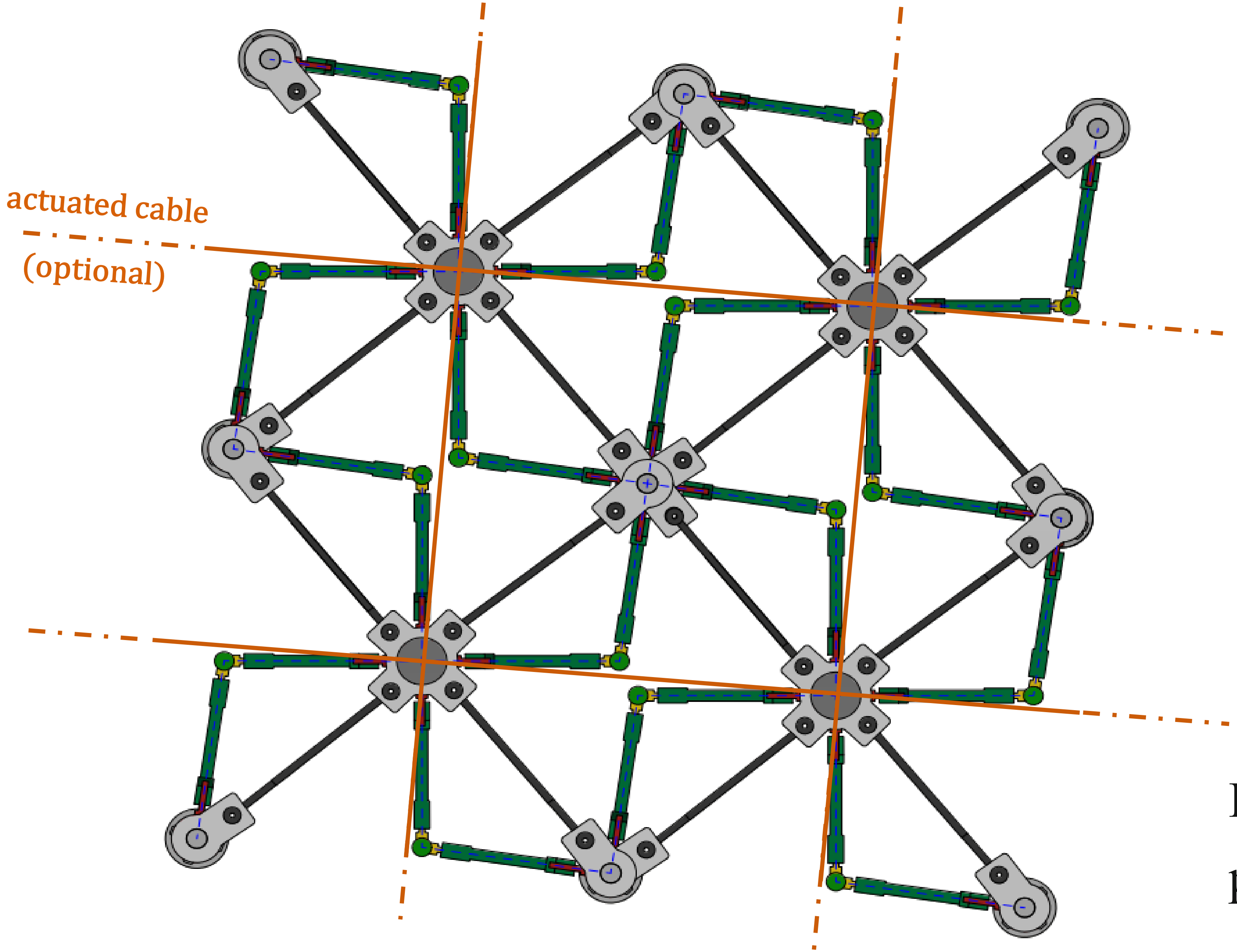
CONCLUDING REMARKS - 1

- 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

- Overall, we conclude that the biomimetic isolators analyzed in this study are classified as highly tunable seismic isolators that can be manufactured with customized properties using optimal geometries and sustainable materials easily available around the world
- It is possible to tune the displacement capacity acting only on the internal architecture of the unit cell;
- The uniaxial tension regime of the tendons is suitable for a class of materials much larger than the elastomeric products employed in rubber bearings;
- The SSI does not require heavy industry and is easily repaired by replacing the tendons after an extreme seismic event.

FUTURE WORK



Development of
periodic metaisolators

Gantt chart

	2018-2019		2019-2020		2020-2021			2021-2022	
Activities	Nov-July	Aug-Oct	Nov-July	Aug-dec	Nov-Apr	May-July	Aug- Oct	Nov-dec	Jan
Bibliographic research									
Preliminary design									
Modelling									
Actual manufacturing of model									
Experimental testing and validation of results									
Publication of results									
Thesis compilation									

Publications

- *F. Fraternali, N. Singh, A. Amendola, G. Benzoni, G.W. Milton, A biomimetic sliding–stretching approach to seismic isolation, Nonlinear Dynamics (2021) 1-13.*
- *A. Amendola. N. Singh, F. Santos, G. Benzoni, F. Fraternali., Innovative dissipative devices with tensegrity architecture and super elastic behaviour for the seismic protection of structures, EURODYN 2020- XI International Conference on Structural Dynamics, 2020.*
- *I. Farina, N. Singh, F. Colangelo, R. Luciano, G. Bonazzi, F. Fraternali, High-performance nylon-6 sustainable filaments for additive manufacturing, Materials 12(23) (2019) 3955.*
- *N. Singh, F. Santos, A. Amendola, F. Fraternali and A. Micheletti., Seismic metamaterials with tensegrity architecture, in: M.F. M. Papadrakakis (Ed.) 8th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering, Athens, Greece, 2021.*
- *N. Singh, A. Amendola, G. Benzoni, and F. Fraternali, 2021, January. Computational modeling of the seismic response of tensegrity dissipative devices incorporating shape memory alloys. In 14th WCCMECCOMAS Congress 2020 (Vol. 100).*

Thank you for your attention!

More information on the presented research is available on my personal website and the research websites of my supervisor and co-supervisors.

I will be very glad to answer your questions.