On the usability of polymer-based artificial tendons for elastic energy storage in active ankle prostheses

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Context

Vast majority of ankle prostheses are **passive** → cannot provide the net positive energy required during walking like a biological ankle

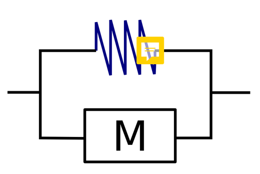
Leading to an **assymetric** gait and to comorbidities such as back pains and osteoarthritis

Development of **active** prostheses. ~~To~~ relax the requirements of the actuator, elastic elements are placed in **parallel** (PEA) and/or in **series** (SEA) with the actuator. Generally, carbon leaf or steel spring are used

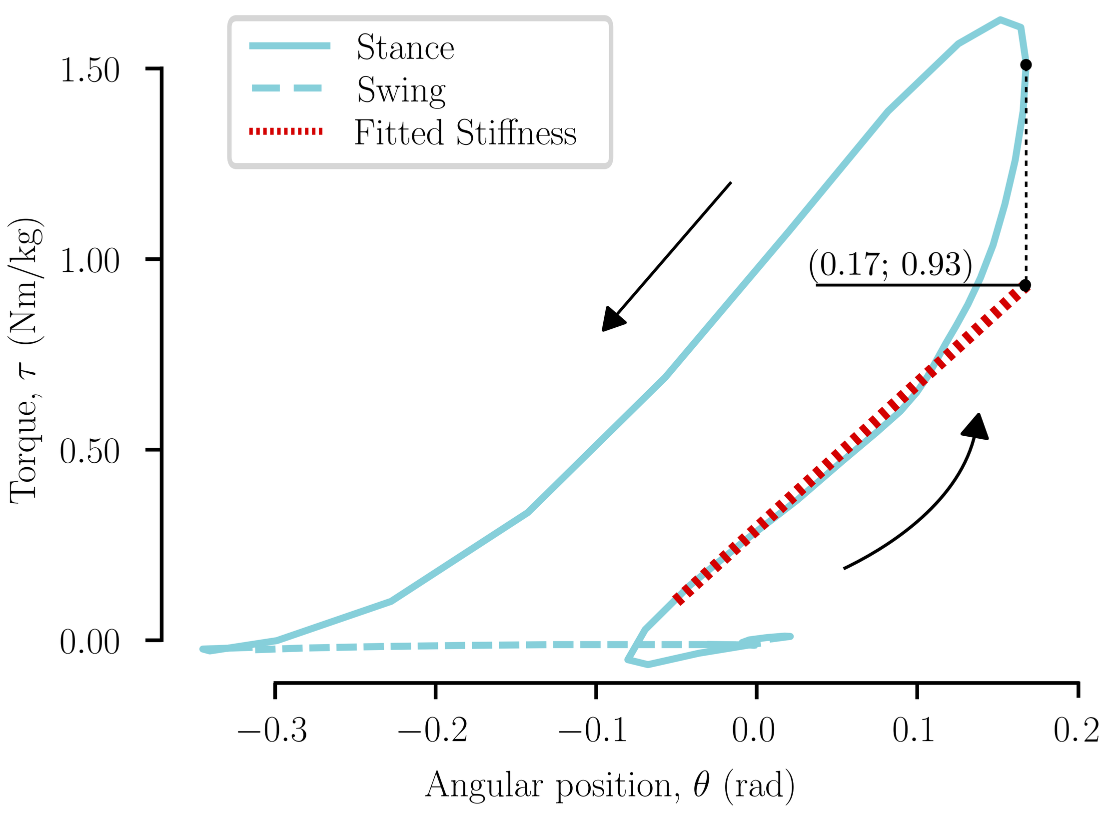
Investigation whether **polymer-based ropes**, which are **light and compact**, are good candidates to act as elastic energy storage in an ankle prosthesis

Problem Statement

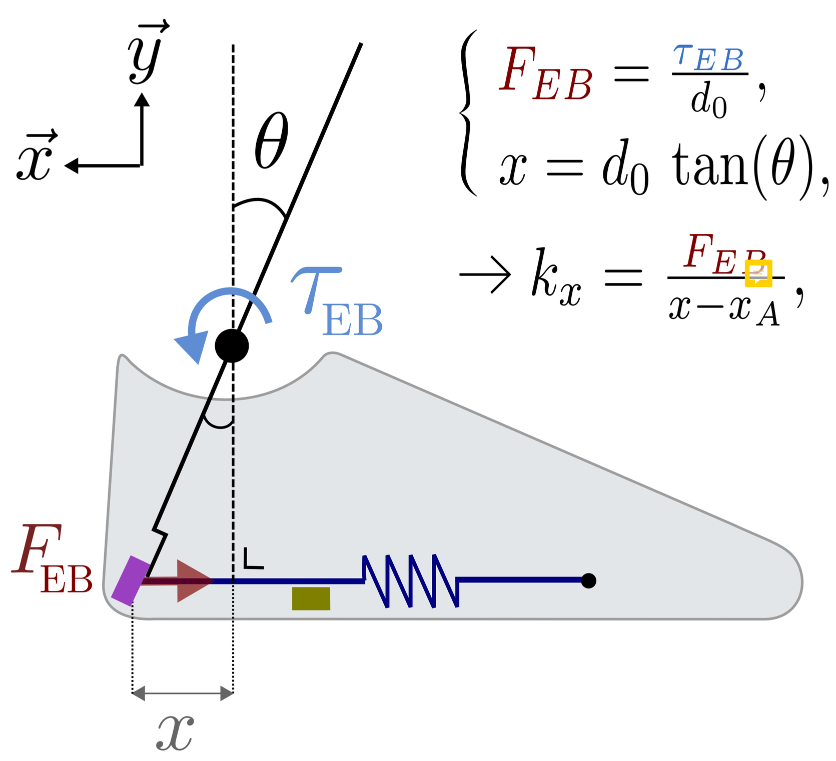
- Application: ELSA active ankle prosthesis, with a SEA [1]



→ ideal **stiffness** is found by interpolating the rising edge of the torque-position curve [1]



- Establishing the design specifications of the ropes based on the constraints of a **biological ankle**



$$\begin{cases} F_{EB} = \frac{\tau_{EB}}{d_0}, & (kN) \\ x = d_0 \tan(\theta), & (mm) \end{cases}$$

$$\rightarrow k_x = \frac{F_{EB}}{x - x_A}, \quad (kN/mm)$$

1. Stretching forces up to 1.48 kN
2. Equivalent linear stiffness of about 0.15 kN/mm
3. ~~A~~ strain of about 13 %
4. ~~A~~ high energy efficiency

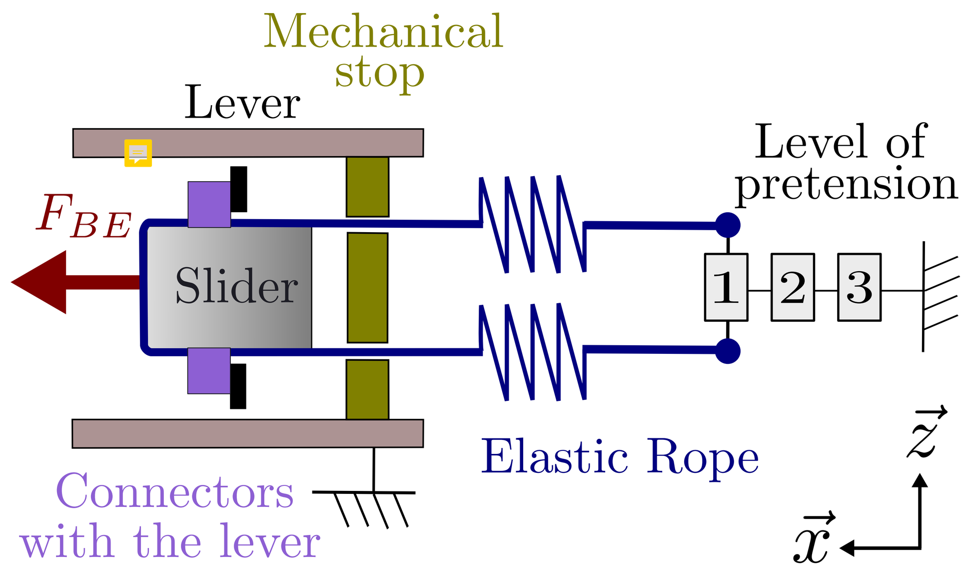
Material Selection

Polyamide and **Polyester** braided ropes → high breaking strength and elongation at break

	PE	PA1	PA2
Material	Polyester	Polyamide	Polyamide
⌀ (mm)	3	3	3
# Strands	8	16	8

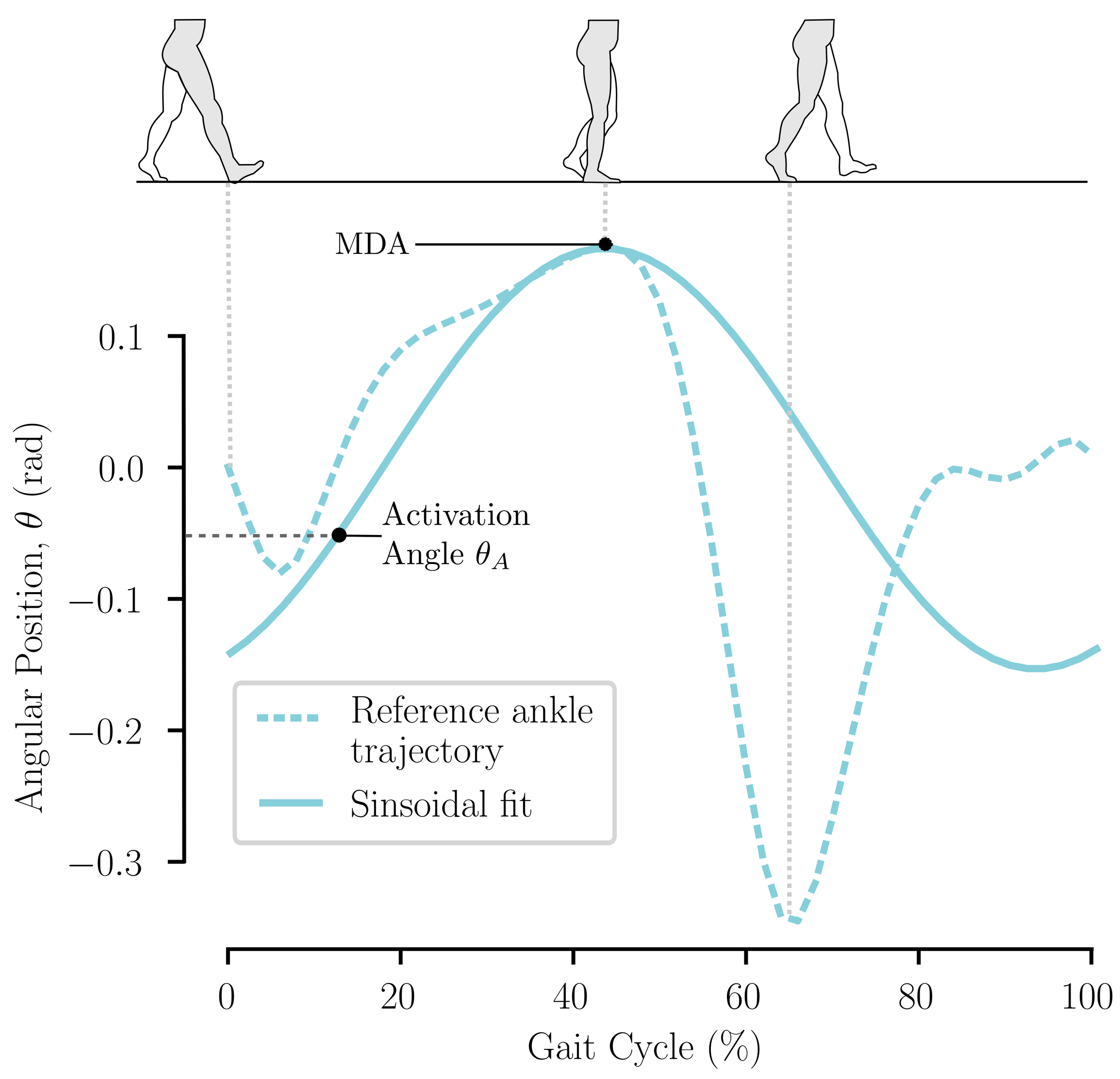
Mechanical Setup

- Test bench driving the lever arm of the prosthesis in **cyclical movements**
- Top view of the setup :



- The pretension ~~of the rope~~ can be tuned with 3 different levels
- Sinusoidal trajectory matching the typical movement executed during the stance phase of walking :

$$\theta_{ref}(t) = A \sin(2\pi f t) + A_0$$



- Experiment 1 : Largest achievable force. Loading the 3 ropes with the highest level of pretension.
- Experiment 2 : Changing the level of pretension. Loading the rope PE with the 3 levels of pretension.
- Experiment 3 : Changing the cycle frequency. Comparision between slow (0.2Hz) and fast~~er~~ (1Hz) walking frequency

Energy efficiency

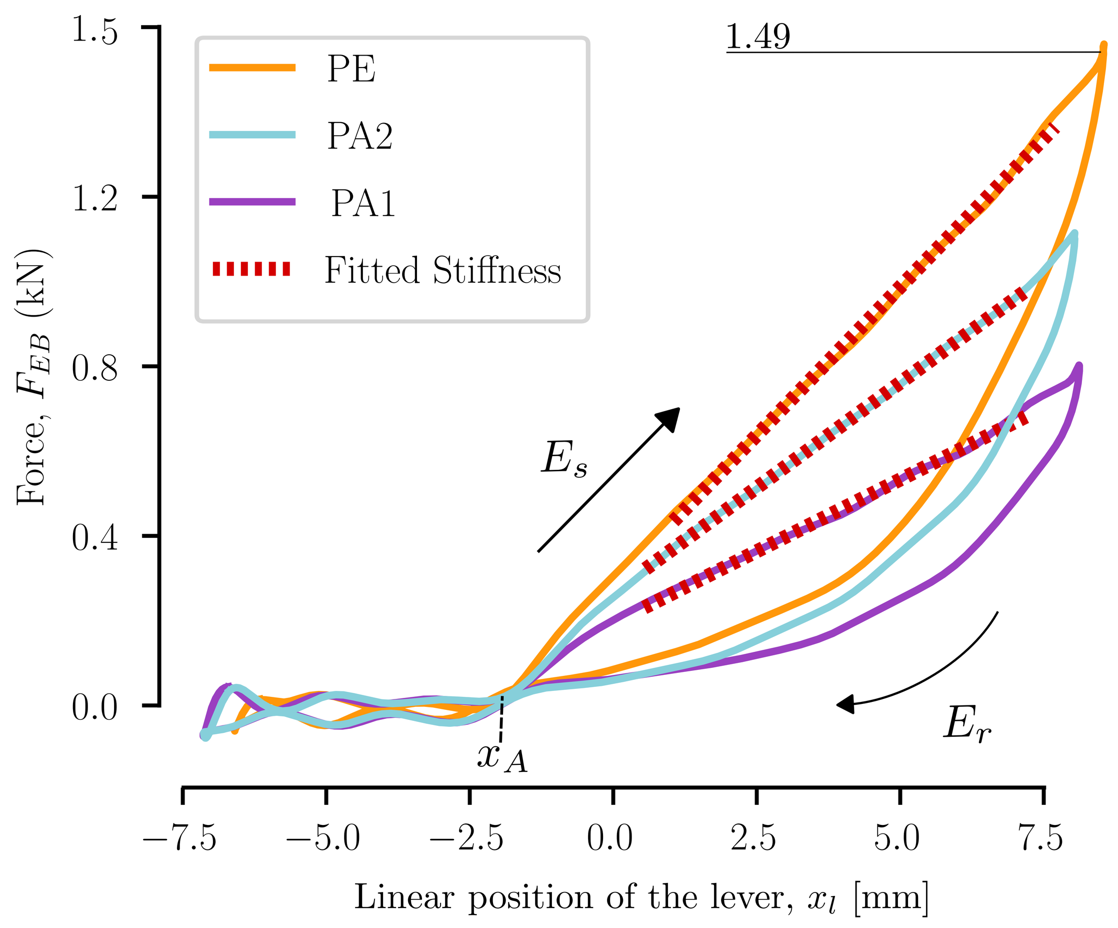
$$E = \int P_m(t)dt = \int F_{EB}(t)\,\dot{x}(t)dt, \quad (J)$$

$$\eta = \frac{E_r}{E_s} \times 100, \quad (\%)$$

Results

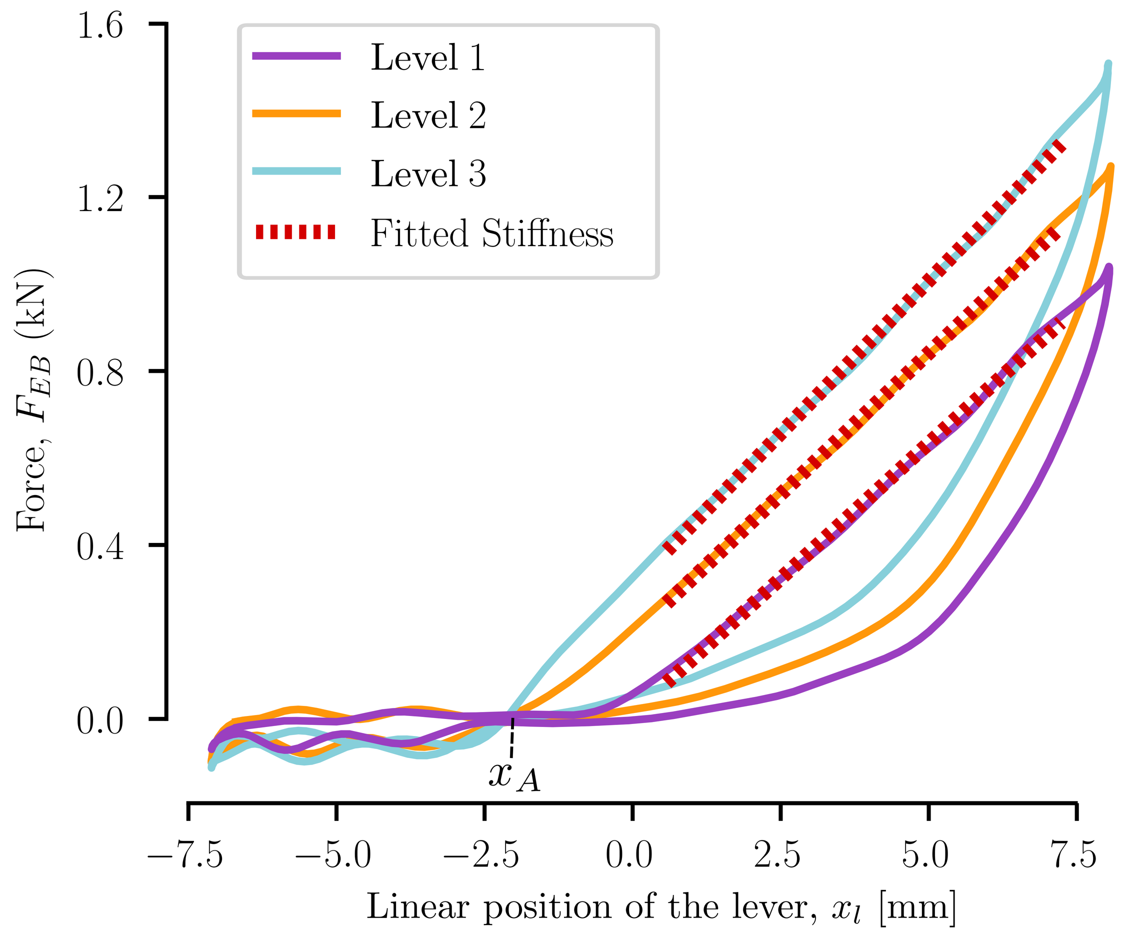
Experiment 1

- Energy efficiency of about **50%** for the 3 ropes → ~~High~~ **energy losses**
- Linear stiffness of PE = **0.14 kN/mm**
- Too low stiffness for PA1 and PA2 → do not achieve the target force, ~~more~~ appropriate for users with lower body weight



Experiment 2

- Rising phase of the tensioning phase ~~have~~ different profiles :
  - Low pretension → slack
  - High pretension → bump
- Higher prentension level → the rope is tauter and achieves higher force



Experiment 3

- Estimated stiffness and energy efficiency very similar → no effect of the frequency

Conclusion

- Polymer-based ropes fulfil several criteria for a typical application of ankle prosthesis because they are **light**, **compact**, and have a **high yield strength**
- Nevertheless for the 3 experiments, **hysteresis** in the force vs. position relationship is large. About 50% of the stored elastic energy is **lost** in friction during the cycle
- Further research should be conducted to improve their efficiency in returning the previously stored elastic energy

[1] Heremans F., et al. "Bio-inspired design and validation of the Efficient Lockable Spring Ankle (ELSA) prosthesis," *IEEE 16th International Conference on Rehabilitation Robotics (ICORR)*, 2019.