IeCAT 2020

Biomimetic Design of a Planar Torsional Spring to an Active Knee Prosthesis Actuator using FEM Analysis

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Summary

Introduction

- Motivation
  - Increasing number of hospitalizations due to transfemoral amputations [1]
  - Transfemoral amputees' locomotion [2,3]
    - Expends more metabolic energy
    - Overcompensates the movement with the intact member

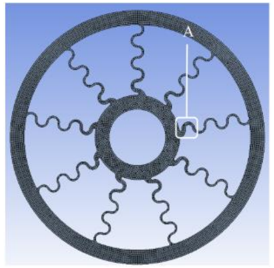
    } Long term damages
  - The need to develop better active lower-limb prostheses [3-7]
    - Recover the leg movements introducing positive power
    - Series Elastic Actuators: greater environment-actuator interaction

Introduction

- Series Elastic Actuators (SEA) [3,5-7]
  - Develop Compliant elements to tolerate impacts
    - Linear springs, torsion springs, etc
  - Spring for a knee prostheses [8]
    - Passive store mechanical energy
      - Daily activities have a lot of dissipative phases
    - Match the Knee quasi-stiffness of flexion and extension stages of the stance phase
      - The moment-angle relationship is approximately linear
    - Characteristics
      - Lightweight
      - Compact: Planar torsional springs

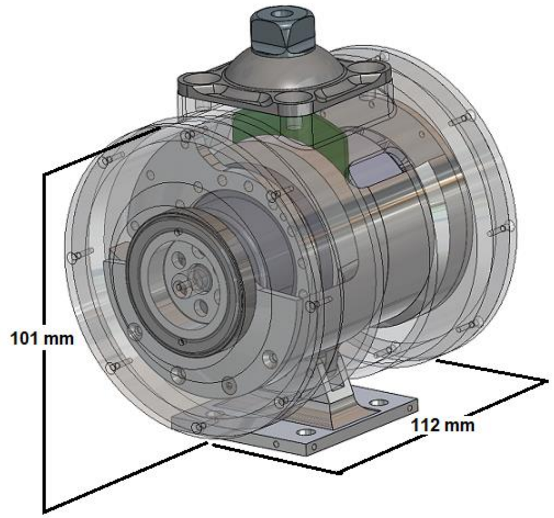
Introduction

- SEAs: Planar Torsional Springs
  - Flexible component or linear springs tangentially arranged
  - Dos Santos et al., 2015 [9]- Flexible component
    - $\tau_{max} = 15\ Nm$
    - $S_C = 200\ Nm/rad$
    - AISI 6150 Steel
  - Wang et al., 2017 [10] - Flexible component
    - $\tau_{max} = 30\ Nm$
    - $S_C = 288.5\ Nm/rad$
    - Maraging Steel 300
  - Tsagarakis et al., 2009 [6] - linear springs
    - $\tau_{max} = 40\ Nm$
    - $S_C = 150\ Nm/rad$



Mechanical Design

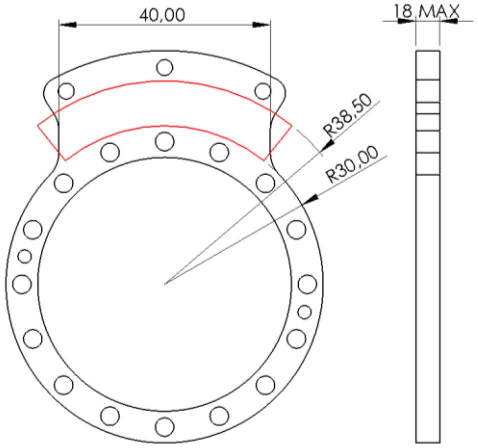
- The Knee Prosthesis
  - Assist a person with 1.71m and 71.6kg [11]
  - Actuator components
    - EC60 Flat 200W – Maxon Motor, Switzerland
    - CSG 17-50-2A-R – Harmonic Drive SE, Germany
  - Characteristics*
    - Nominal torque: 27 Nm at 64 rpm
    - Positive peak torque: 80 Nm
    - Resistive peak torque: 90 Nm
    - 1.53 kg

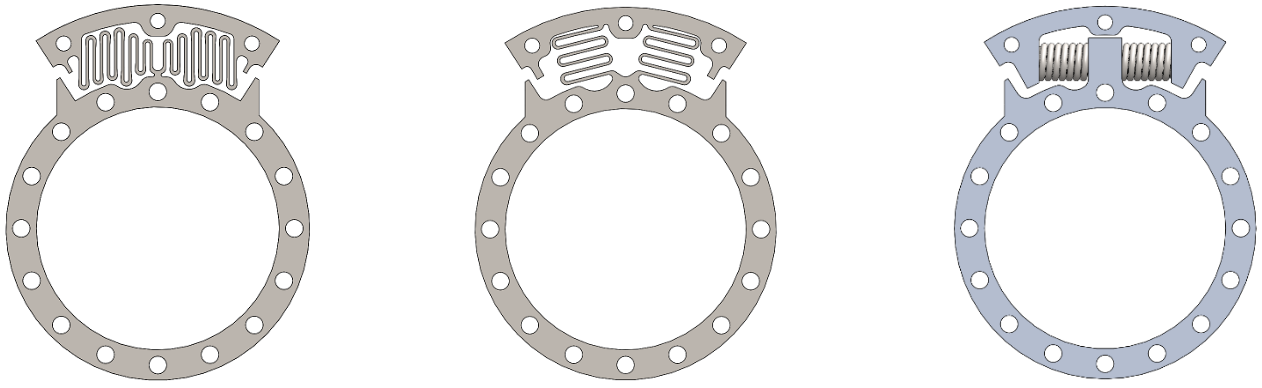


*Without the efficiency factors.

Mechanical Design

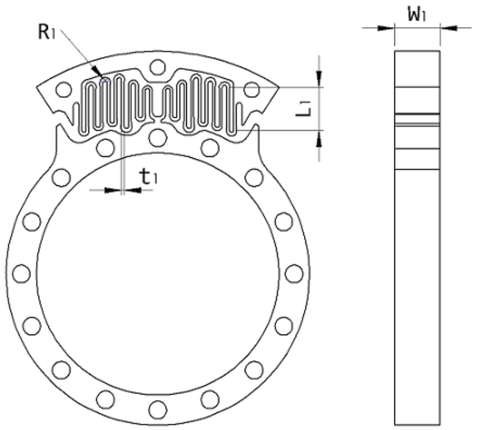
- Torsional Spring Design
  - Shamaei et al, 2013 [8] - Stiffness Target
    - 246 Nm/rad
  - Limitations
    - 0.200 kg
    - Width ≤ 18 mm
    - Limited available space (highlighted region)
  - Three proposed geometries

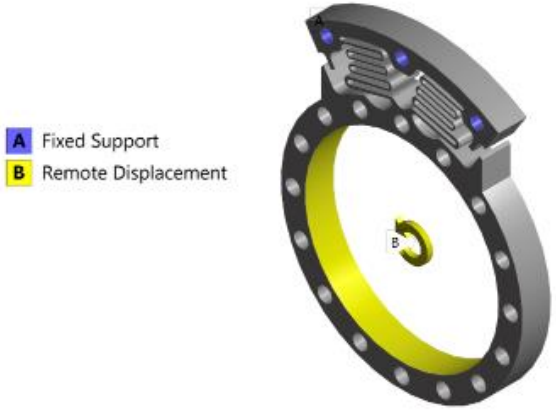




Mechanical Design

- Torsional Spring Analysis – First and Second Design
  - Parameters
    - R_1, t_1, L_1, W_1
  - Boundary conditions in the FEM Analysis
    - Spring Analysis – Maximum Stress and Stiffness = Moment reaction/Angular displacement
    - Mechanical end stop Analysis – Stress when the Moment reaction reaches 90 Nm





Mechanical Design

- Torsional Spring Analysis – First and Second Design
  - Material Selection
    - Alloys [12,13]
      - AISI 4340 Steel
      - AISI 6150 Steel
    - FEM Analysis
      - Stiffness
      - Safety Factor = 1.8
    - Heat Treatment [12]
      - Austempering: Greater fatigue life than Q&T for stresses higher than the fatigue limit
      - Quenching & Tempering

Table 1. Mechanical properties of the two alloy steels.

Alloy Steel	Elasticity Modulus	Poisson's Ratio	Tensile Yield Strength	Tensile Ultimate Strength
AISI 4340[1,2]	212 GPa	0.30	1475 MPa	1595 MPa
AISI 6150[1]	205 GPa	0.29	1225 MPa	1240 MPa

[1] Reference [12] [2] Reference [13]

Mechanical Design

- Torsional Spring Analysis – Third Design
  - Tsagarakis et al., 2009 [6] - Linear Springs Stiffness Target
    - $k_s = 2k_a \cdot \left(R^2 + \frac{r_s^2}{3}\right) \cdot (2cos^2\theta_s - 1)$
      - k_s: Torsional spring stiffness
      - k_a: Linear spring stiffness
      - R: Radius where the spring is fixed
      - r_s: External radius of the spring
      - θ_s: Angular displacement
    - Manufacturers' catalogs
      - Search springs that fit the space limitations
    - Recalculate the Torsional spring stiffness

Results

- Material Selection – First Design
  - The spring parameters are fixed
  - Calculus of the stiffness
  - Maximum allowable rotation based on the safety fator
  - Heat Treatment
    - Austempering: Greater fatigue life than Q&T for stresses higher than the fatigue limit

✓ Austempered AISI 4340 Steel

Table 2. Results of the material selection analysis.

Alloy	Maximum rotation	Spring Stiffness
AISI 4340	2.5 °	74 Nm/rad
AISI 6150	2.2 °	72 Nm/rad

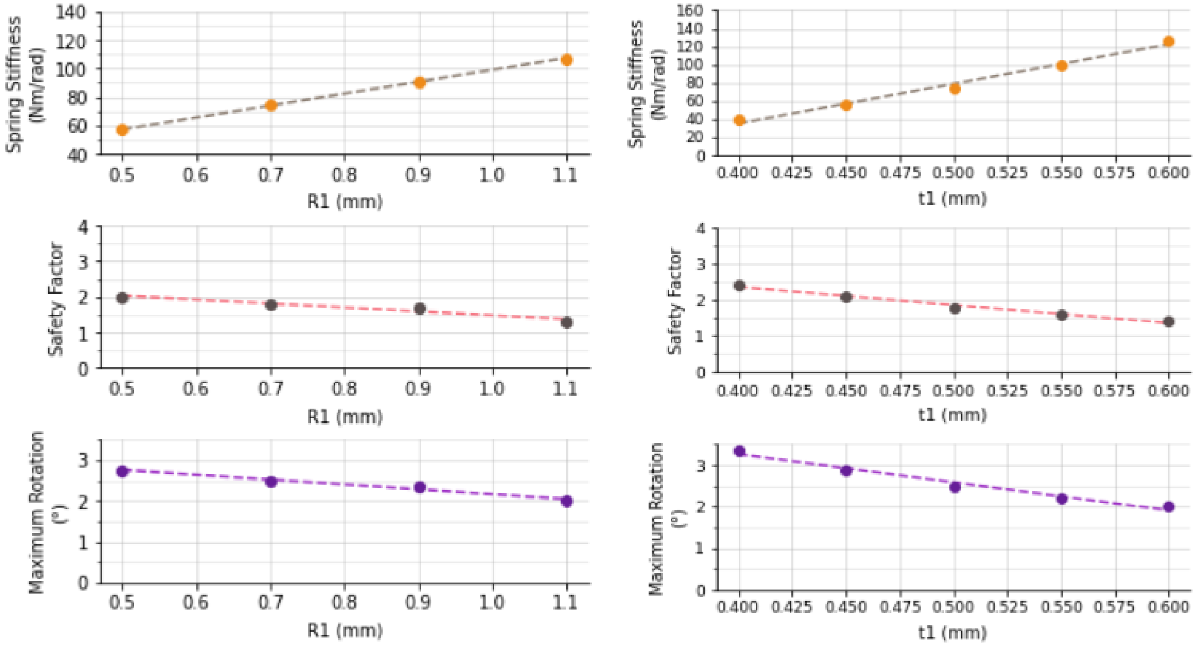
Results

- Spring Analysis – First Design
  - R_1 Variation
    - W_1 = 10 mm; t_1 = 0.5 mm
    - L_1 : varies in function of R1 and the available space
    - ✓ R_1 = 0.7 mm

↑ R_1 ↑ Stiffness ↓ Safety fator & Max. Rotation

  - t_1 Variation
    - W_1 = 10 mm; R_1 = 0.7 mm; L_1: fixed
    - ✓ t_1 = 0.5 mm

↑ t_1 ↑ Stiffness ↓ Safety fator & Max. Rotation



k_s = 74 Nm/rad; Rotation up to 2.50 °

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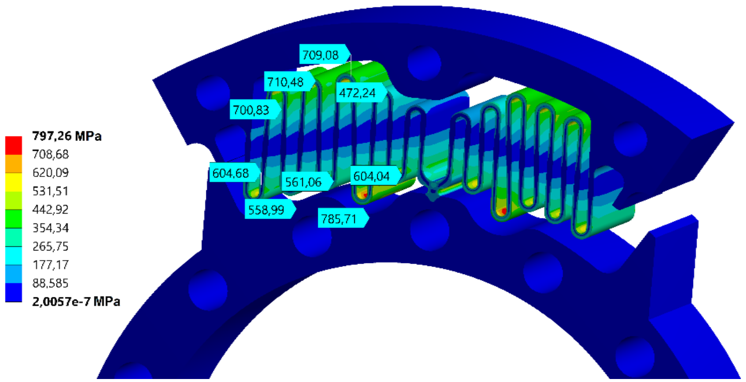
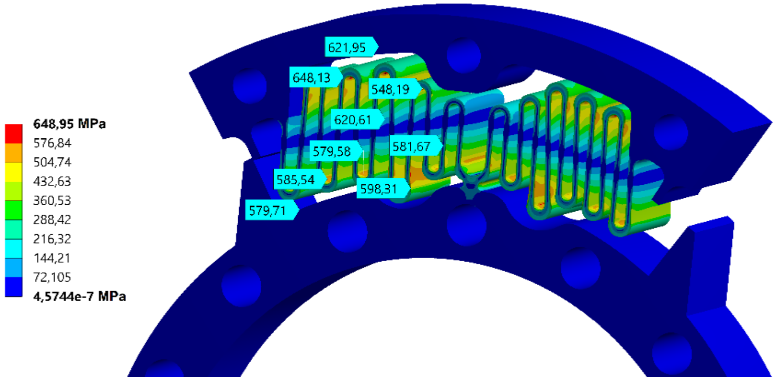
Results

- Spring Analysis – First Design
  - Manual enhancements - Probes
    - Augment in Stiffness and Safety Factor
    - Possibility to increase the maximum rotation to 3.20 °
    - Spring mass/width : 0.00927 kg/mm

Before the enhancement



After the enhancement



Stress for a 2.5 ° rotation.

k_s = 106 Nm/rad; Rotation up to 3.20 °

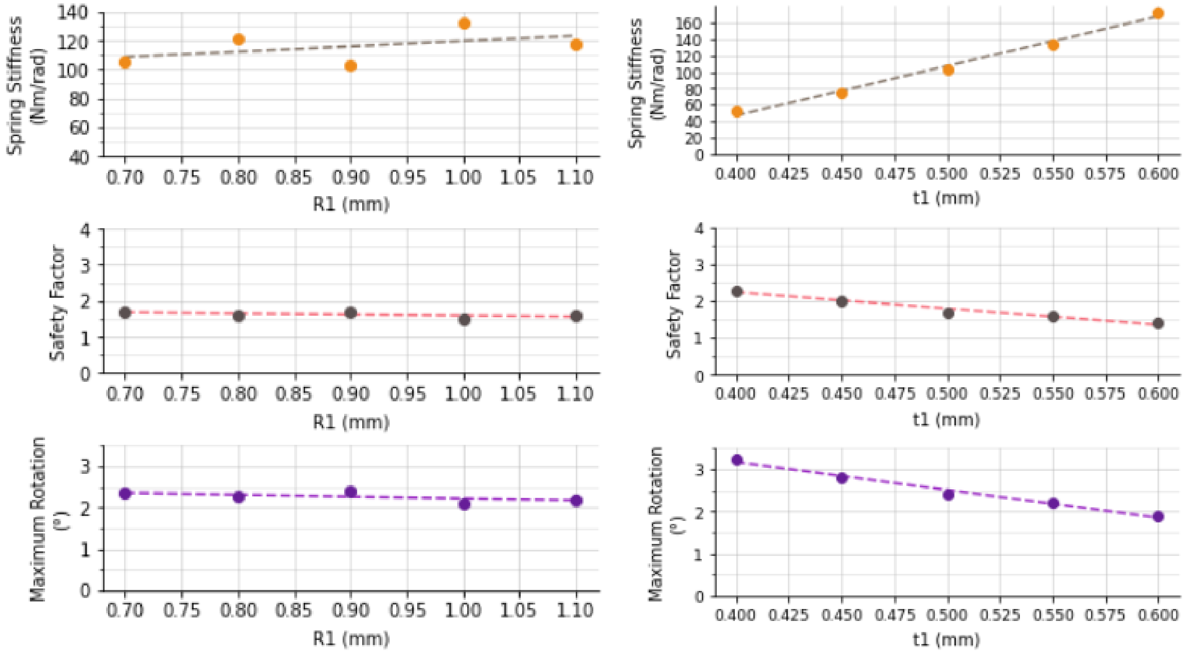
Results

- Spring Analysis – Second Design
  - R_1 Variation
    - W_1 = 10 mm; t_1 = 0.5 mm ; L_1 = 8.5 mm
    - ✓ R_1 = 0.9 mm

↑ R_1 ↑ Stiffness ↓ Safety fator & Max. Rotation

  - t_1 Variation
    - W_1 = 10 mm; R_1 = 0.9 mm; L_1 = 8.5 mm
    - ✓ t_1 = 0.5 mm

↑ t_1 ↑ Stiffness ↓ Safety fator & Max. Rotation

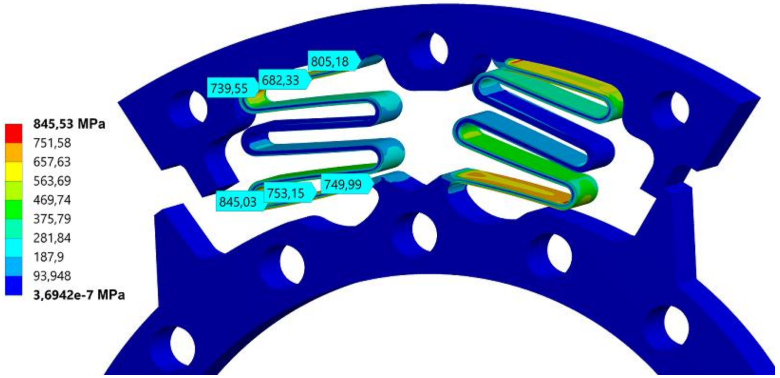


k_s = 103 Nm/rad; Rotation up to 2.40 °

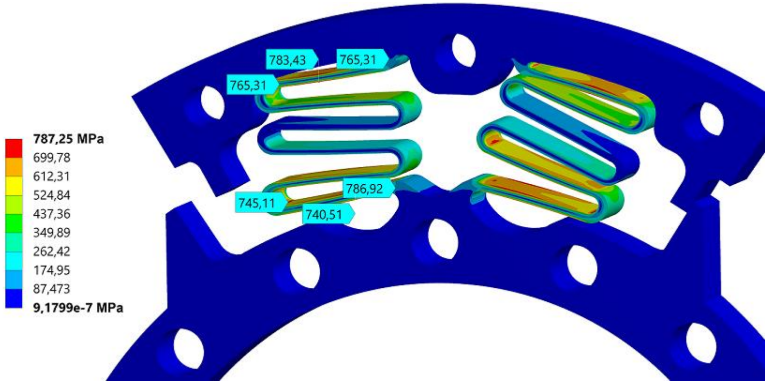
Results

- Spring Analysis – Second Design
  - Manual enhancements - Probes
    - Augment in Stiffness and Safety Factor
    - Possibility to increase the maximum rotation to 2.50 °
    - Spring mass/width : 0.00898 kg/mm

Before the enhancement



After the enhancement



Stress for a 2.5 ° rotation.

k_s = 149 Nm/rad; Rotation up to 2.50 °

Results

- Spring Analysis – Third Design
  - k_a Overvaluation
    - R = 34 mm; r_s = 0 mm; θ_s= 10 °; k_s = 246 Nm/rad
    - ✓ k_a = 113 N/mm
  - Catalogs' springs

Table 3. Linear compression springs characteristics.

	External diameter	Undeflected Length	Maximum deflection	Stiffness (k_a)
Spring 1	8.1 mm	17.5 mm	7.3 mm	16.81 N/mm
Spring 2	8.1 mm	12.2 mm	4.7 mm	26.43 N/mm

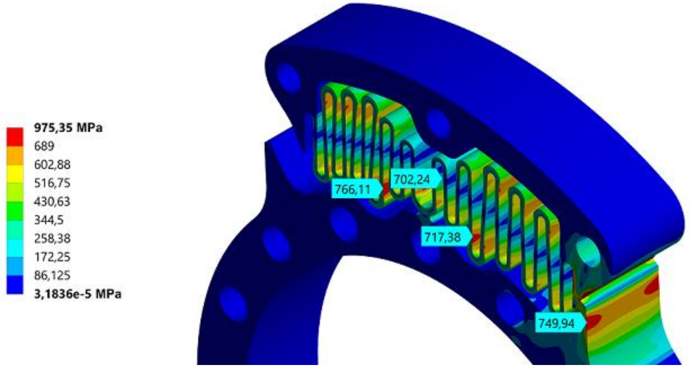
- k_{s1} = 38.15 Nm/rad
- k_{s2} = 60.80 Nm/rad

k_s = 60.8 Nm/rad; Rotation up to 3.96 °

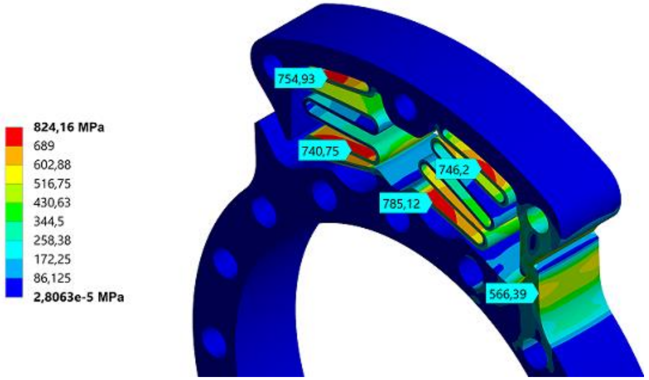
Results

- Mechanical end Stop Analysis – First and Second Design
  - Inner Ring rotates until the moment reaction reaches 90 Nm
    - Only one spring
    - Evaluate the maximum stress

W_1 = 9 mm



W_1 = 8.5 mm



Discussion and Conclusions

- The Springs Stiffnesses are lower than the Knee quasi-stiffness
  - Parallel association of at least two springs – limited by the maximum width (18 mm)
  - Lower stiffness means that the user will feel like falling in heel strike

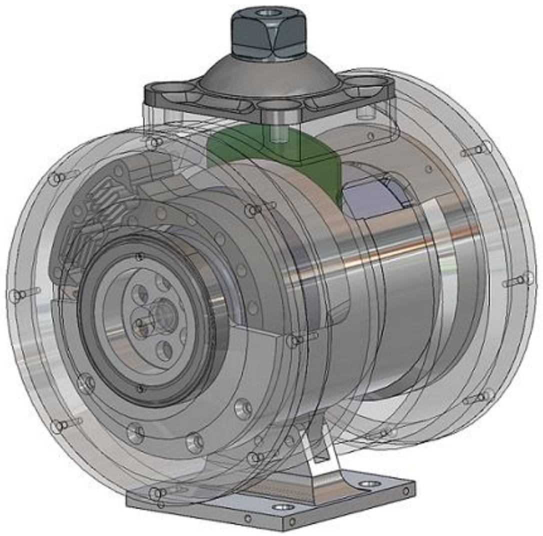
  - The second design
    - ✓ The intermediate mass and width
    - ✓ The torsional spring constant matches the knee quasi-stiffness
    - ✓ Lower stresses with greater torque entries - more fatigue life

Parameters	First Design	Second Design	Third Design
W_1	9 mm	8.5 mm	8.1 mm
Number of springs	2	2	2
Maximum Rotation	3.20 °	2.50 °	3.96 °
Total Spring Mass	0.167 kg	0.153 kg	0.066 kg
Total Spring Stiffness	191 Nm/rad	250 Nm/rad	122 Nm/rad

Discussion and Conclusions

- The SEA Knee Prosthesis
  - Two parallel springs of the Second Design
  - The mass is up to 1.660 kg

- Future work
  - Manufacture and test the real torsional spring
    - Check the stiffness
    - Discover the fatigue life
  - Compare the performance of the rigid actuator and the SEA



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