Universität Stuttgart

Bioinspired pneumatic muscle spring units mimicking the human motion apparatus: benefits for passive motion range and joint stiffness variation in antagonistic setups

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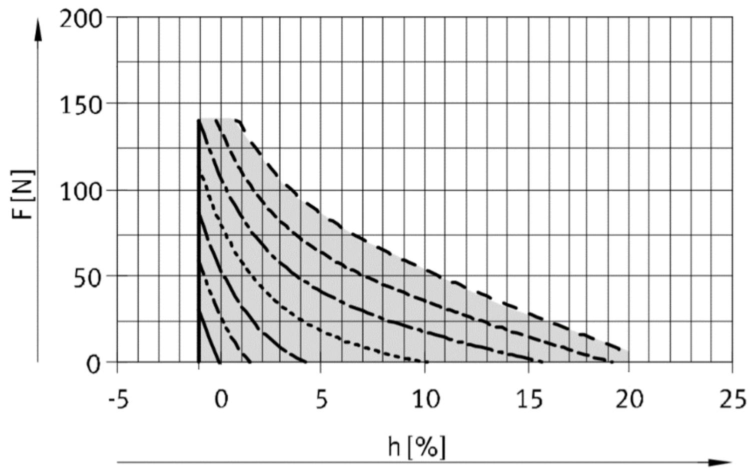
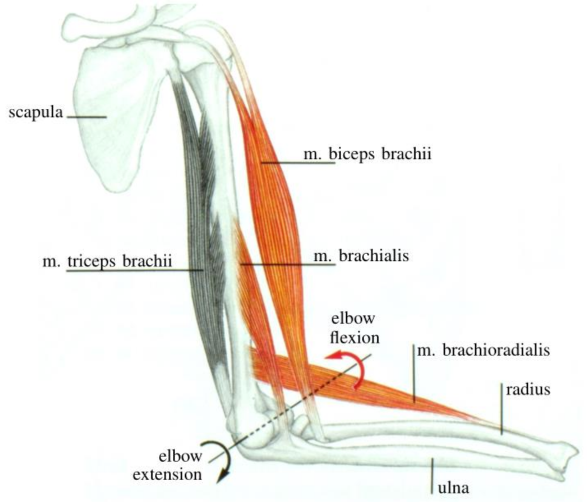
Pneumatic actuated muscle (PAM)



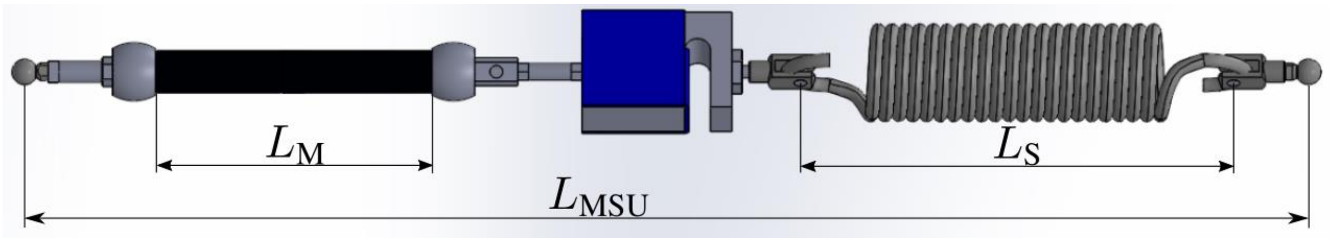
Source: Festo AG & Co.KG, “*Fluidic muscle dmsp datasheet*” 2016

Biological agonist antagonist setup (AAS)

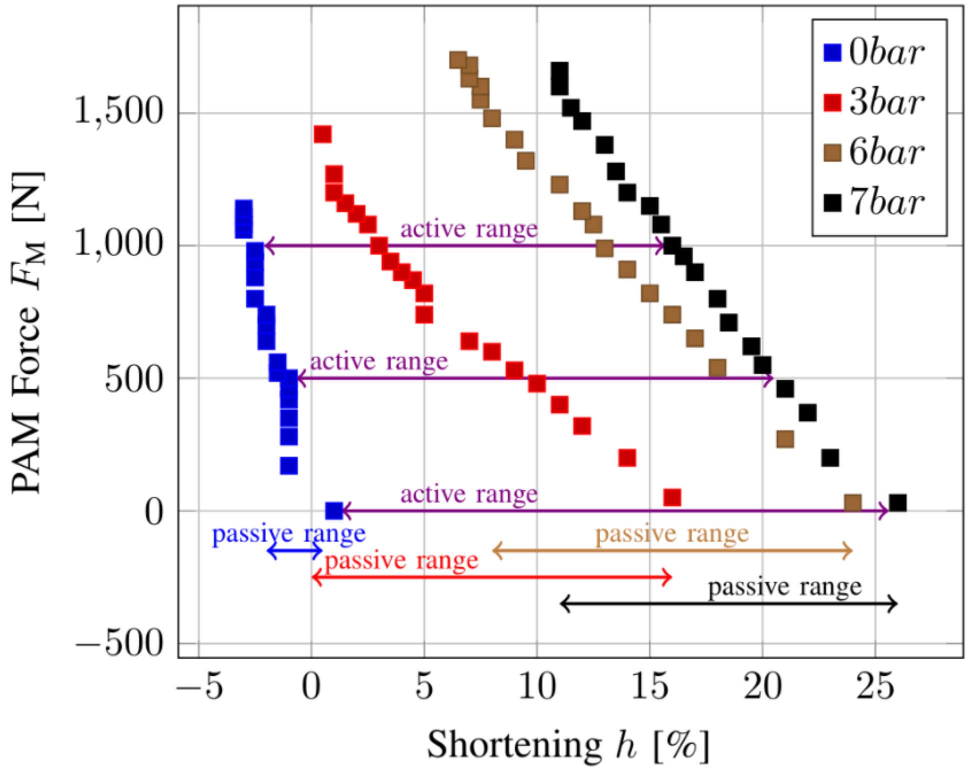


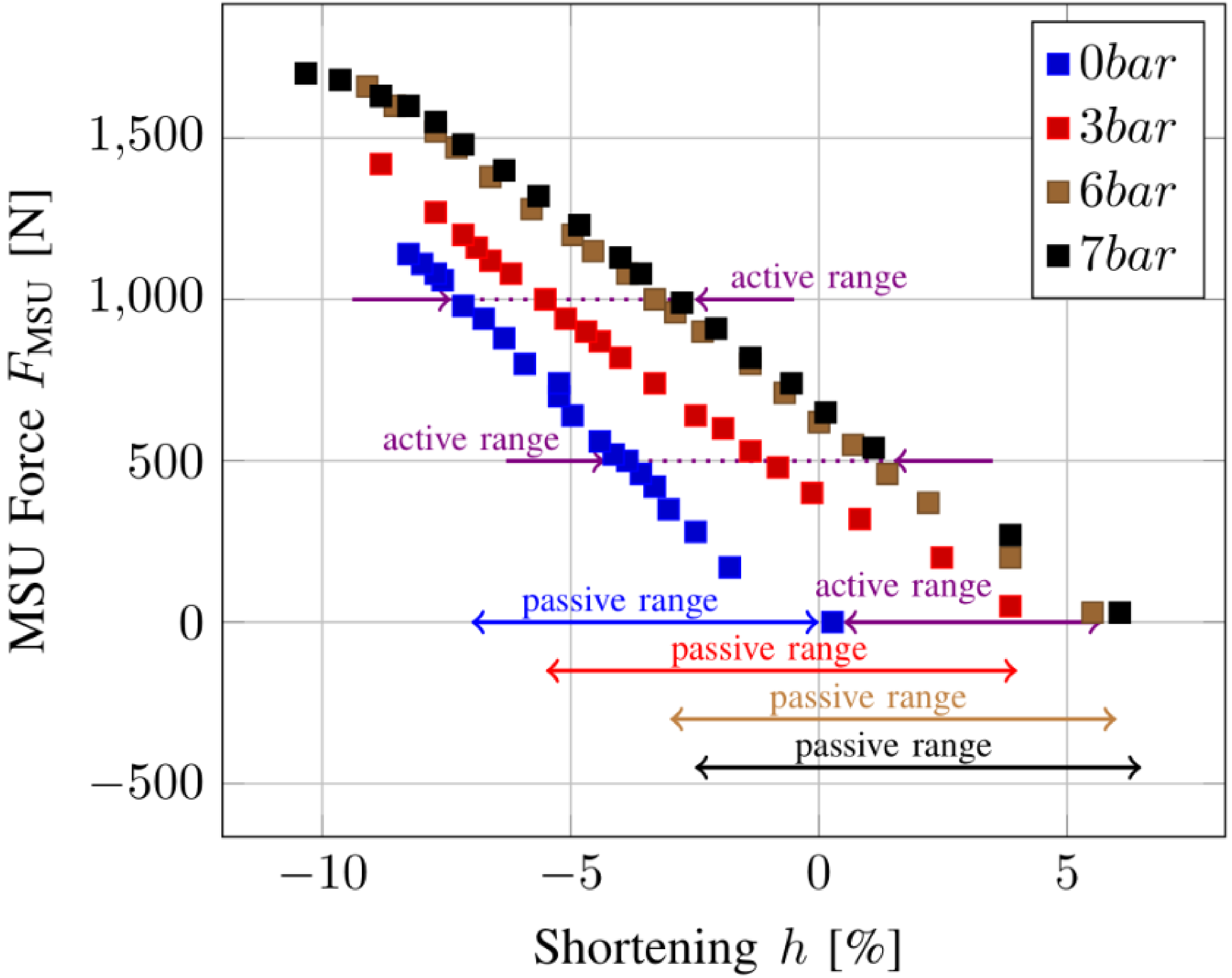
Source: Johannes W Rohen, Chihiro Yokochi, and Elke Lütjen-Drecoll. “*Anatomie des Menschen - Fotografischer Atlas der systematischen und topografischen Anatomie*“ Schattauer Verlag, Stuttgart, 7. überarb. aufage edition, 2010

Muscle spring unit (MSU)



Active and passive characteristics



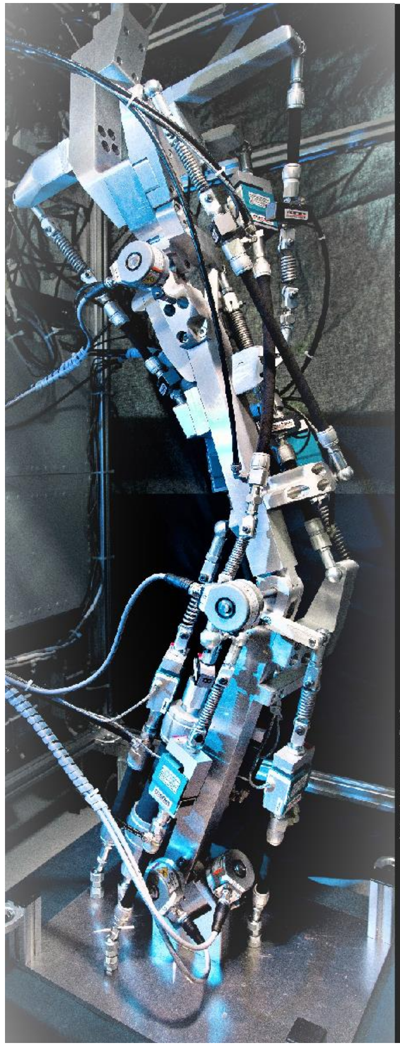


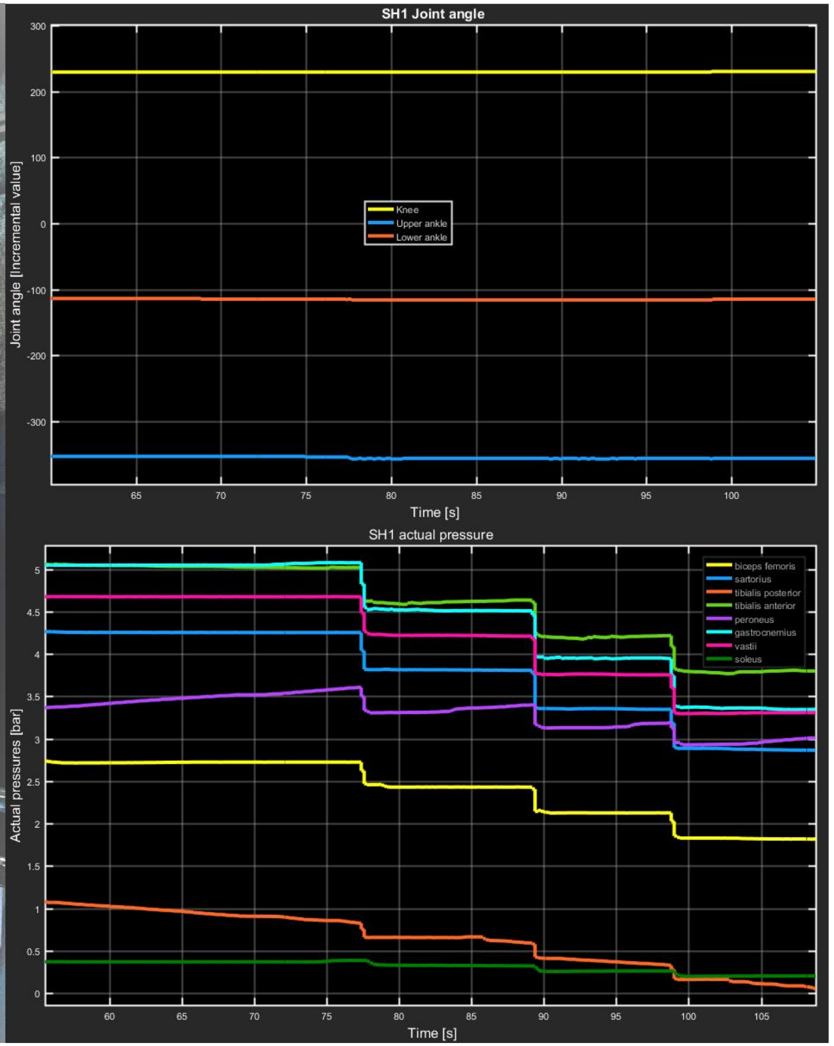
Stuttgart humanoid 1 (SH1)

- 13 MSUs representing the muscles m. glutaeus maximus, m. adductor (lumped), m. rectus femoris, m. iliopsoas, m. glutaeus medius, m. sartorius, m. tibialis posterior, m. biceps femoris caput breve, m. tibialis anterior, m. biceps femoris caput breve, m. tibialis anterior, m. biceps femoris caput breve, m. tibialis anterior, m. peronaeus, m. gastrocnemius, m. vastii (lumped) and m. soleus

- SH1 has 5 joints with incremental encoders and each MSU has a force sensor included

- SH1 can perform a stable stance with different joint positions without collapsing. A given stance position can be achieved with different levels of co-contraction of the muscles, as illustrated by the two measurement scopes (right)

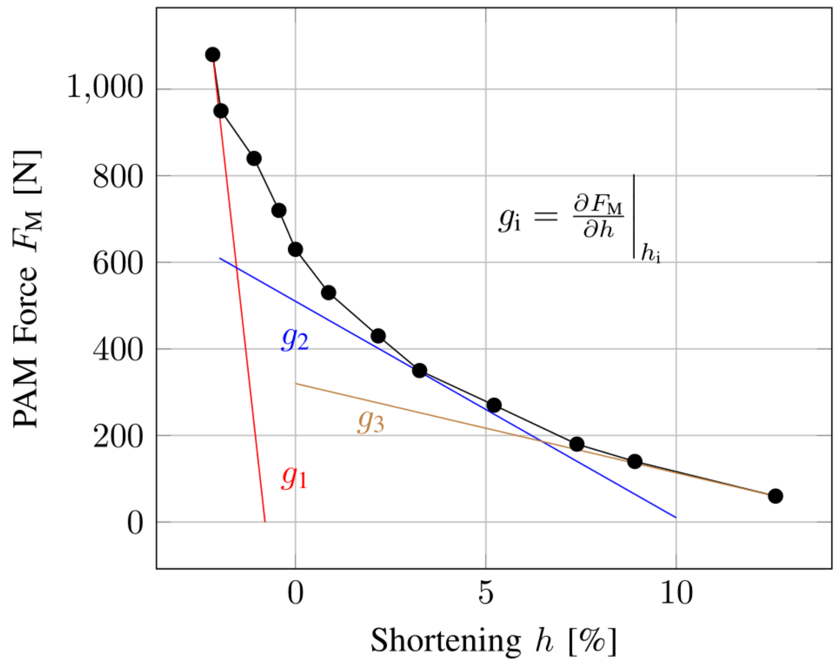




The research question:

Is there a benefit of using MSUs instead of PAMs in an AAS?

Spring as design element:



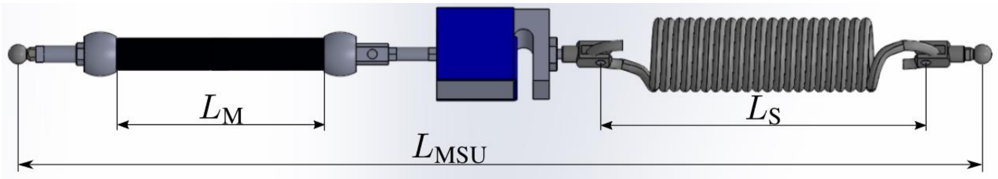
Mathematical model of a PAM by Chou:

Source: Festo AG & Co.KG, “*Fluidic muscle dmsp datasheet*” 2016

$$F_M(P, L_M) = \frac{Pb^2}{4\pi n^2}\left(\frac{3L_M^2}{b^2} - 1\right)$$

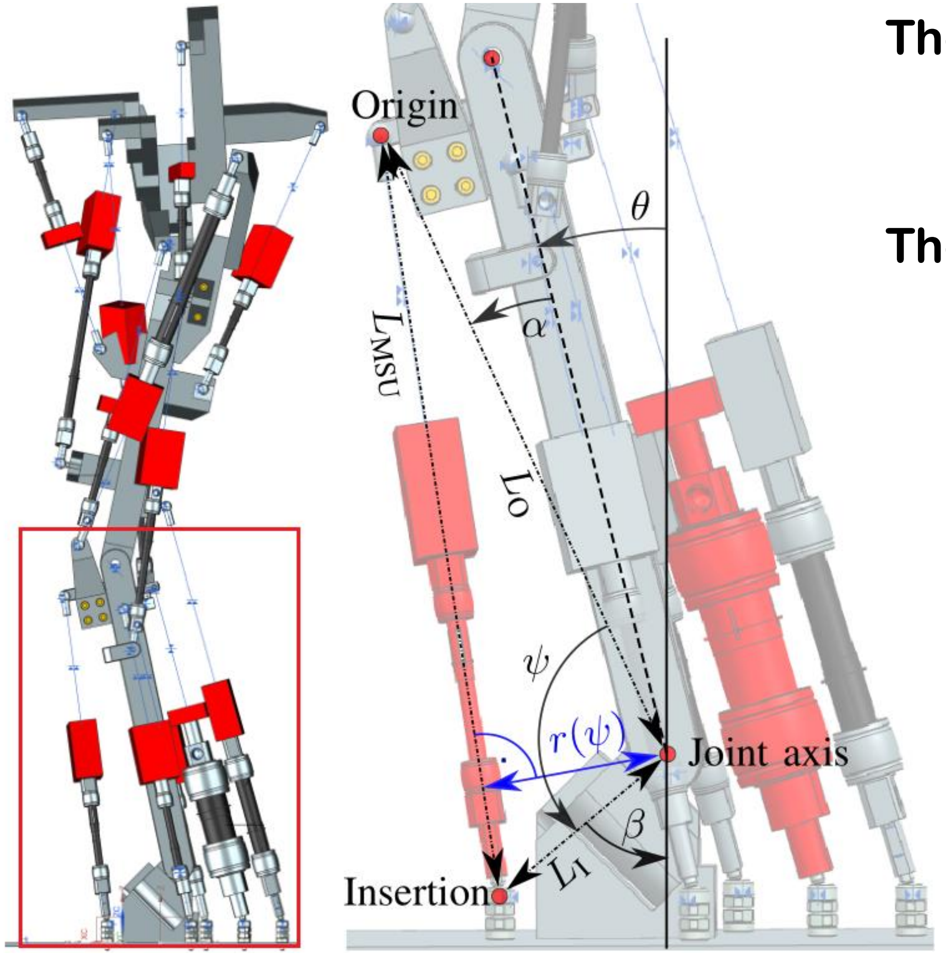
Chou, Ching-Ping and Hannaford, Blake “*Measurement and modeling of McKibben pneumatic artificial muscles*” IEEE Transactions on robotics and automation, 1996

Modified Chou model for a MSU:



$$F_{MSU}(P, L_{MSU}) = \frac{Pb^2}{4\pi n^2}\left(\frac{3(L_{MSU} - \frac{F_{MSU}}{k_S} - L_R)^2}{b^2} - 1\right)$$

M. tibialis and m. soleus of SH1 as an AAS example



The moment arm:

$$r_{MSU}(\psi) = \frac{L_O L_I \sin(\psi)}{\sqrt{L_O^2 + L_I^2 - 2L_O L_I \cos(\psi)}}.$$

The force-pressure-length relation:

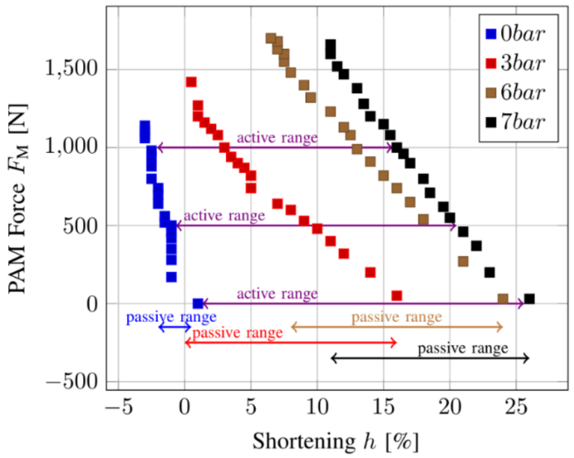
$$F_{MSU}(P, L_{MSU}) = \frac{Pb^2}{4\pi n^2}\left(\frac{3(L_{MSU} - \frac{F_{MSU}}{k_S} - L_R)^2}{b^2} - 1\right)$$

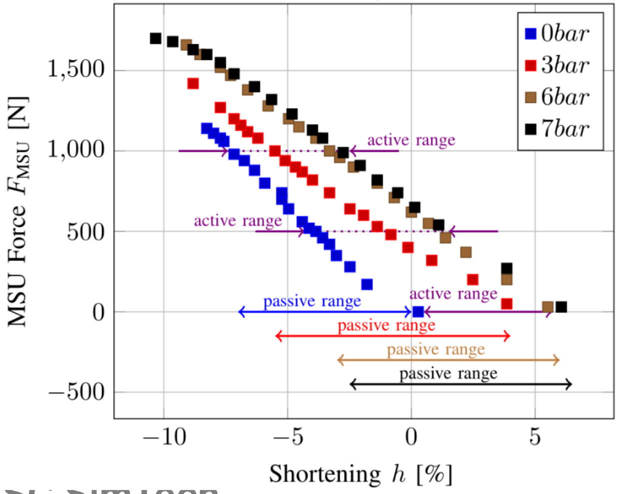
$$F_{MSU}(P, L_{MSU}) = \frac{3P(L_{MSU} - L_R) + 2\pi n^2 k_S^2}{3P} + \frac{k_S}{3P}\sqrt{12Pn^2\pi k_S(L_{MSU} - L_R) + 3P^2b^2 + 4\pi^2 n^4 k_S^2}$$

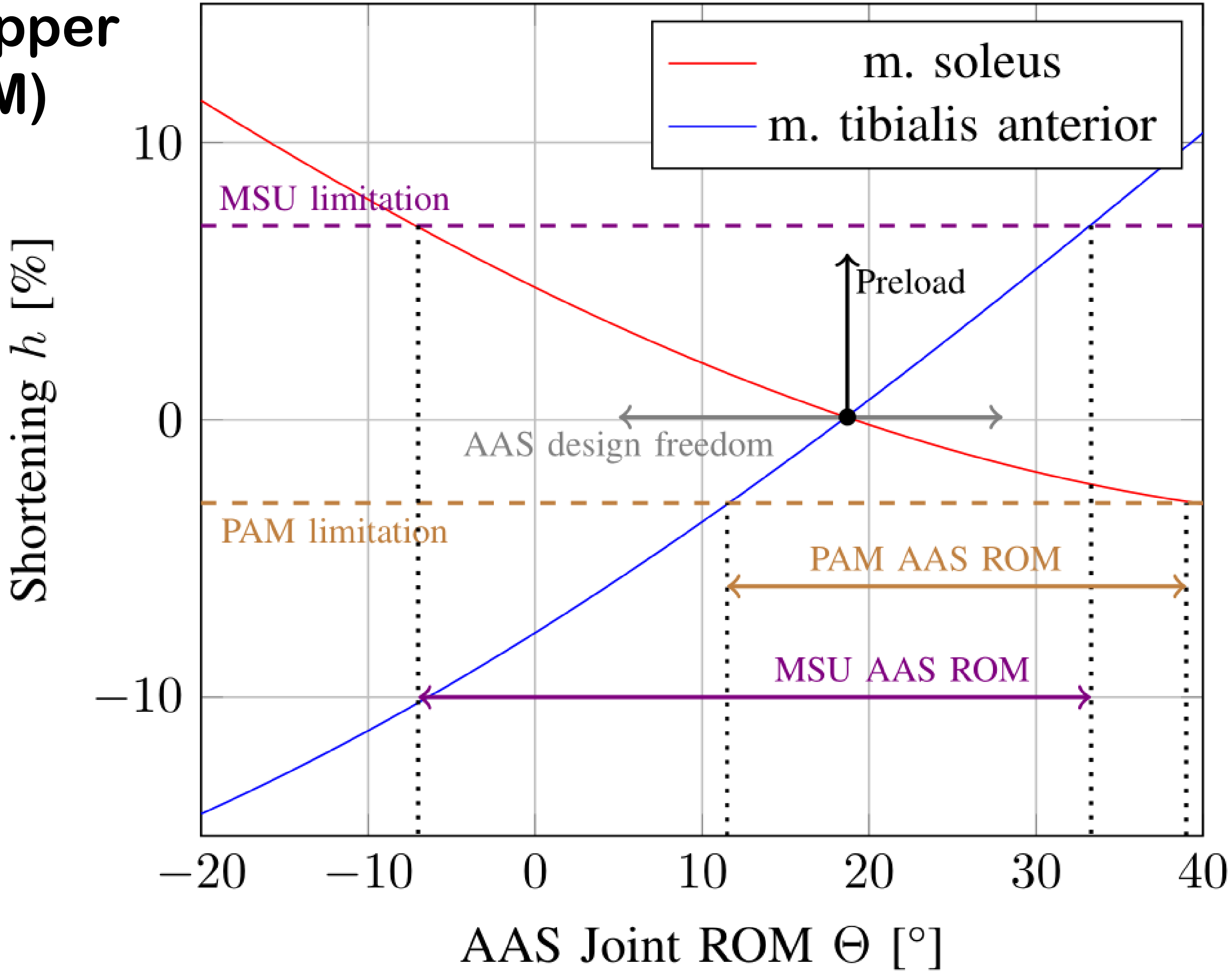
The stiffness of a single MSU:

$$K_{MSU} := \frac{\partial F_{MSU}}{\partial L_{MSU}} \qquad K_{MSU} = \frac{3PL_M k_S}{3PL_M + 2\pi n^2 k_S}.$$

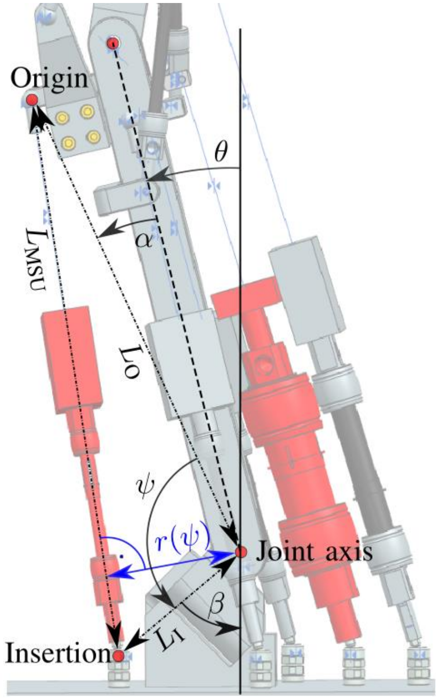
MSU shortening over the AAS upper ankle joint range of motion (ROM)







Adjustable torques over the AAS joint ROM



Resulting torque:

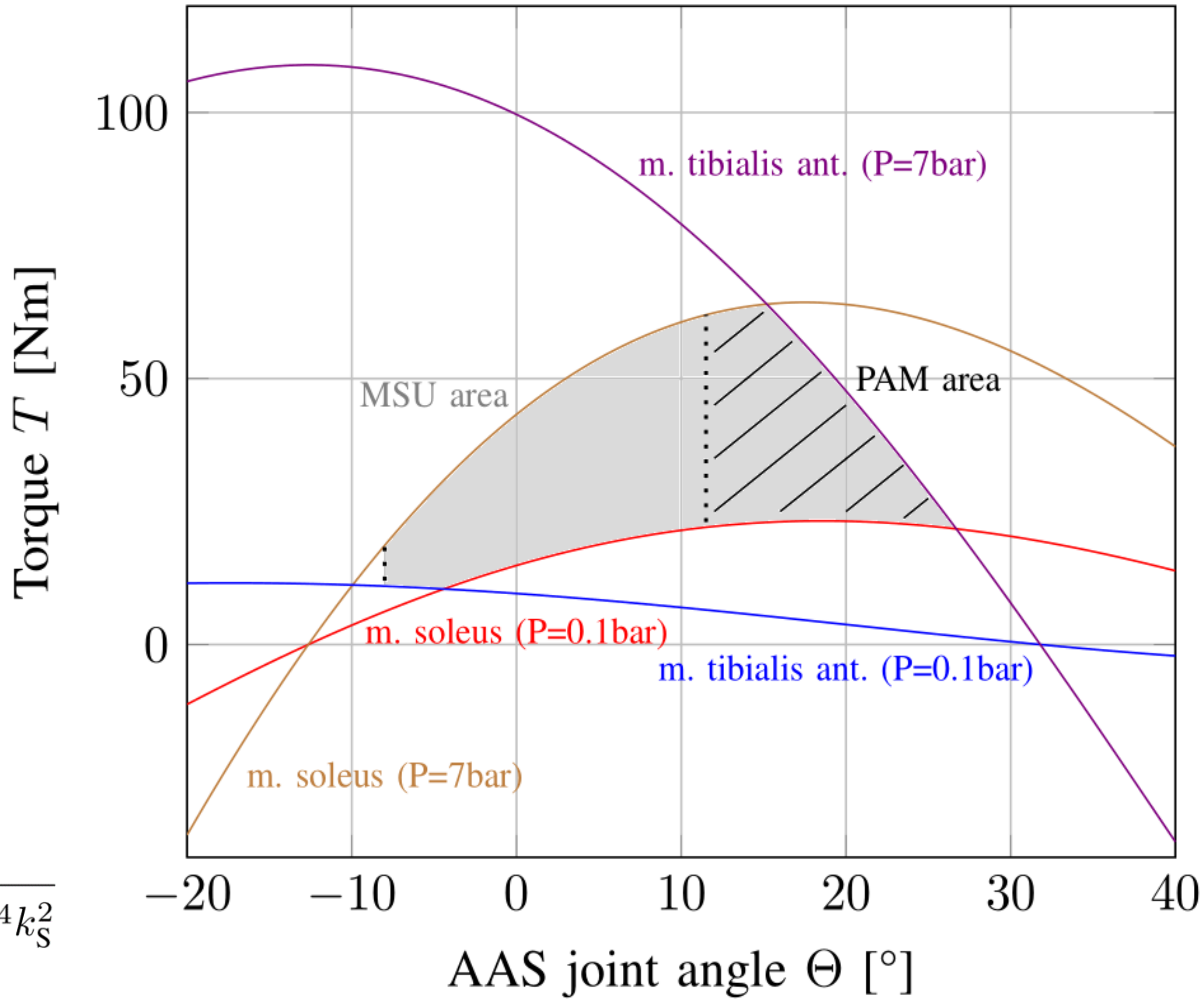
$$T_{\mathrm{A}}(P_{\mathrm{T}}, P_{\mathrm{S}}, \theta) = r_{\mathrm{T}}F_{\mathrm{T}} - r_{\mathrm{S}}F_{\mathrm{S}}$$

Moment arm:

$$r_{\mathrm{MSU}}(\psi) = \frac{L_{\mathrm{O}}L_{\mathrm{I}}\sin(\psi)}{\sqrt{L_{\mathrm{O}}^2 + L_{\mathrm{I}}^2 - 2L_{\mathrm{O}}L_{\mathrm{I}}\cos(\psi)}}.$$

Chou model of MSU:

$$F_{\mathrm{MSU}}(P, L_{\mathrm{MSU}}) = \frac{3P(L_{\mathrm{MSU}} - L_{\mathrm{R}}) + 2\pi n^2 k_{\mathrm{S}}^2}{3P} + \frac{k_{\mathrm{S}}}{3P}\sqrt{12Pn^2\pi k_{\mathrm{S}}(L_{\mathrm{MSU}} - L_{\mathrm{R}}) + 3P^2b^2 + 4\pi^2n^4k_{\mathrm{S}}^2}$$



Adjustable stiffnes over the AAS joint ROM

Resulting joint stiffness:

$$S := \frac{\partial T_A}{\partial \theta}$$

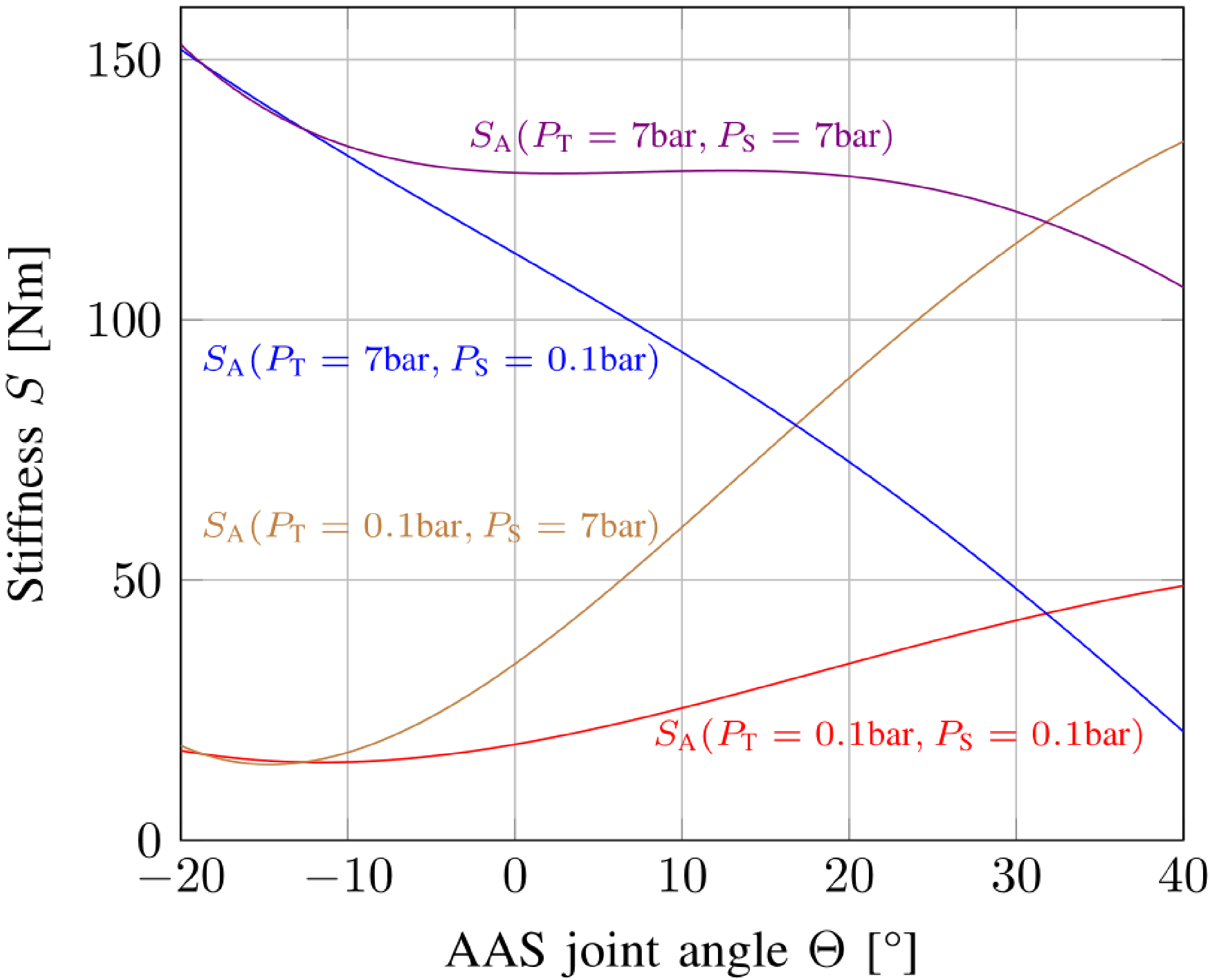
$$S_A(P_T, P_S, \theta) = \frac{\partial r_T}{\partial \theta} F_T + r_T^2 K_T - \frac{\partial r_S}{\partial \theta} F_S - r_S^2 K_S$$

Derivative of the moment arm with respect to the joint angle :

$$\frac{\partial r_{MSU}}{\partial \psi} = \frac{L_I L_O (L_I \cos(\psi) - L_O)(L_O \cos(\psi) - L_I)}{(L_I^2 + L_O^2 - 2 L_I L_O \cos(\psi))}$$

Stiffness of a single MSU:

$$K_{MSU} = \frac{3 P L_M k_S}{3 P L_M + 2\pi n^2 k_S}.$$



Conclusion

- MSUs do not reduce the ROM in an AAS joint (despite a single MSU has reduced active range)

- MSUs increase the available torque range of an AAS joint (compared to a PAM driven joint)

- MSUs can drive AAS joints with minimal stiffness

Thank you for your attention!

Any questions?

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