ADDITIVE 4 BIOMEDICAL

UNIVERSITÀ DEGLI STUDI FIRENZE
DIEF DIPARTIMENTO DI INGEGNERIA INDUSTRIALE

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OPTIMAL DESIGN OF AN OPEN-ENDED BRAIDED STENT USING MOPSO

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SC 09/A3 CoCo AM Additive Manufacturing

ADM ASSOCIAZIONE NAZIONALE DISEGNO E METODI

COMET

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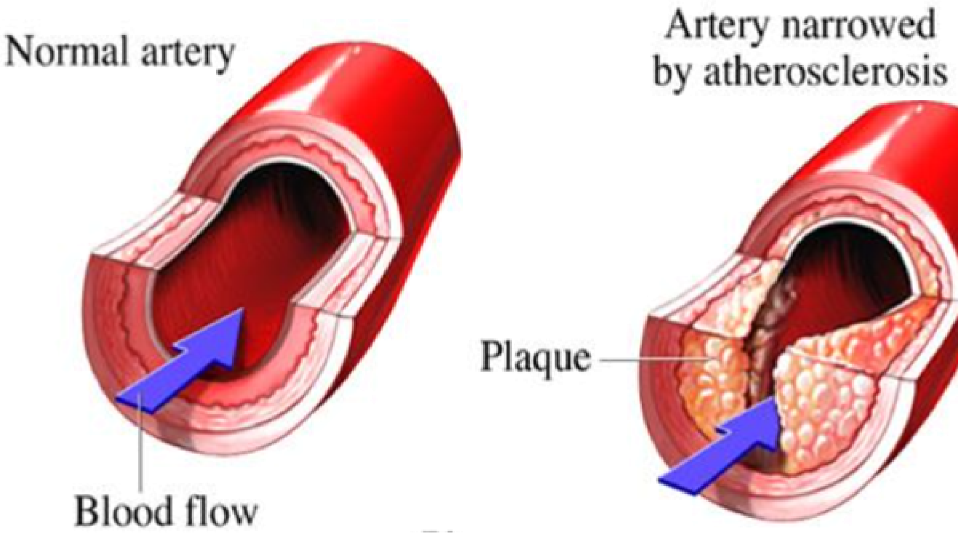
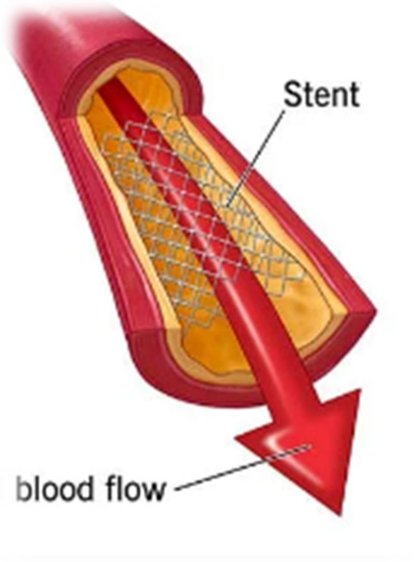
CORONARY ARTERY DISEASE

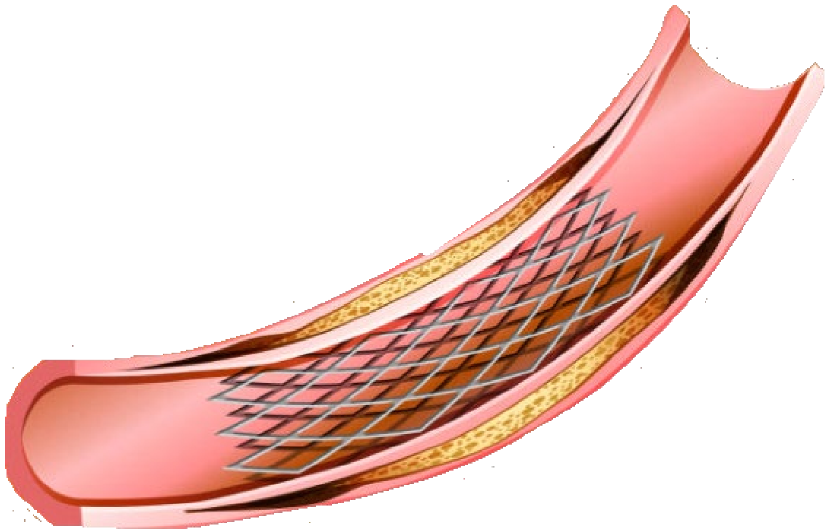
- **Atherosclerosis** : fat or lipid substances are deposited on the arterial wall
- Severe atherosclerosis cause coronary artery disease
- effective treatment method is Percutaneous Coronary Intervention (**PCI**)
- PCI is to unblock and restore blood by placing **vascular stent** on the stenosis





WHAT IS THE STENT?

- A small mesh-like device made of metal
- Acts as a support or scaffold in keeping the vessel open
- helps to improve blood flow to the heart muscle



Ideal Functions And Mechanical Properties of Stents

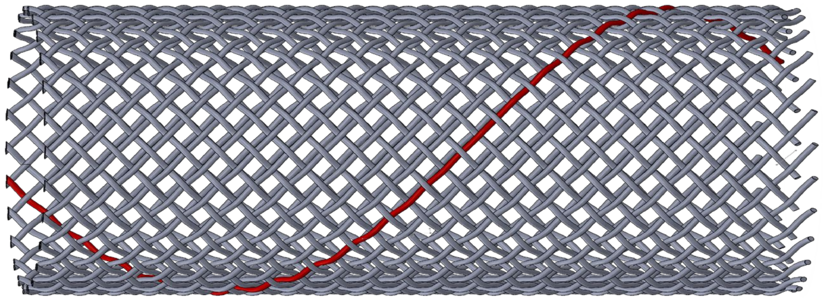
High Radial Stiffness Maintain the vessel open and withstand the periodic load of arteries

Minimum Foreshortening Accurately placed in the position

Maximum Radial Strength Pushed away the blockage and better anchorage

PROBLEM STATEMENT AND ASSUMPTIONS

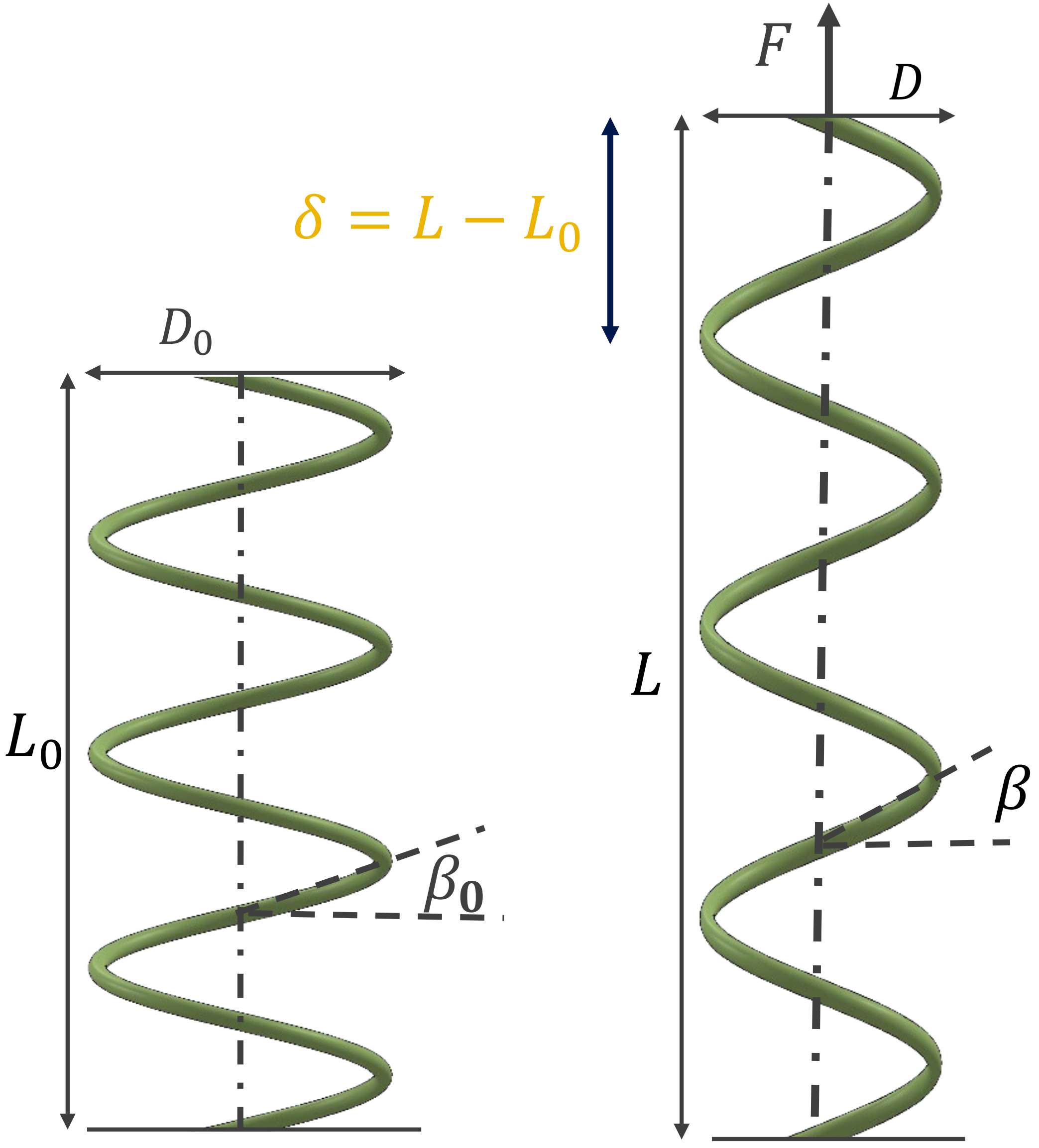
1. Investigate a stent based on Jedwab and Clerc study from technical literature
2. Using the MOPSO algorithm to **enhance mechanical properties**
3. Using AM to **reduce mass/cost** while **maintaining mechanical performance**



ASSUMPTION ON THE STENT BEHAVIOUR

a) It acts as a collection of **independent open-coiled helical springs**.
b) The ends are **fixed against rotating** around the longitudinal axis.
c) It undergoes only **elastic deformation**

STENT GEOMETRY



INITIAL PITCH

$$p_0 = \pi D_0 \tan\beta_0$$

NUMBER OF COILS

$$c = {}^{L_0}/_{P_0}$$

STENT DIAMETER

$$D = \frac{D_0 cos(\beta)}{cos(\beta_0)}$$

STENT LENGTH

$$L = \frac{L_0 sin(\beta)}{sin(\beta_0)}$$

MATERIAL

Linear elastic steel

MECHANICAL PROPERTIES AND ANALYTICAL MODEL

The axial force F exerted on the stent

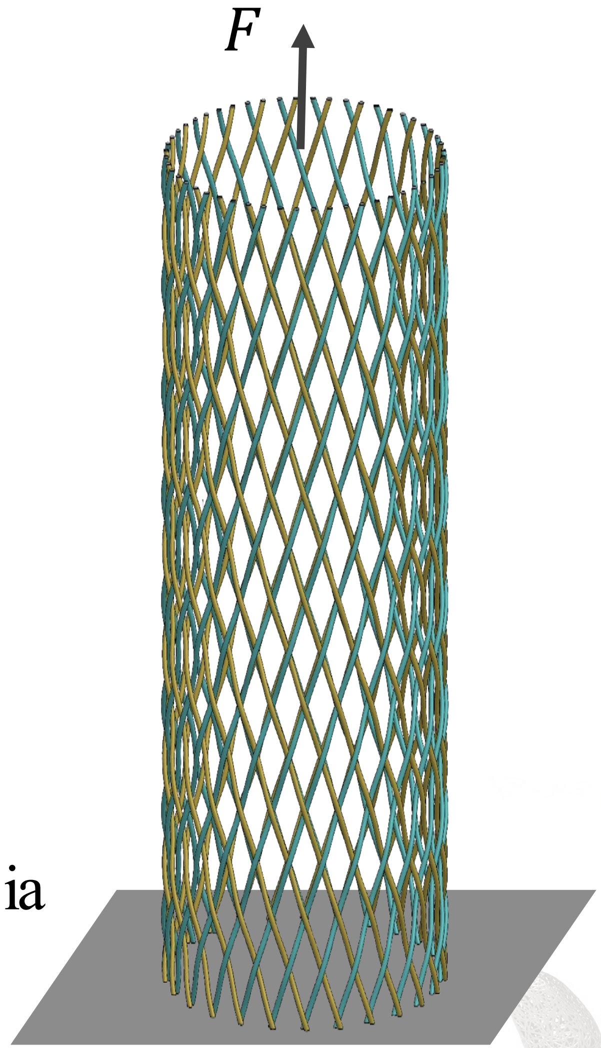
$$F = 2N\left[\frac{GI_P}{K_3}\left(\frac{2sin(\beta)}{K_3} - K_1\right) - \frac{EI.tan(\beta)}{K_3}\left(\frac{2cos(\beta)}{K_3} - K_2\right)\right]$$

$$K_1 = \frac{sin(2\beta_0)}{D_0} \qquad K_2 = \frac{2cos^2(\beta_0)}{D_0} \qquad K_3 = \frac{D_0}{cos(\beta_0)}$$

N : the number of wires

I and $\boldsymbol{I_P}$: the moment of inertia and polar moment of inertia

G and ***E***: the shear modulus and Young's modulus



MECHANICAL PROPERTIES

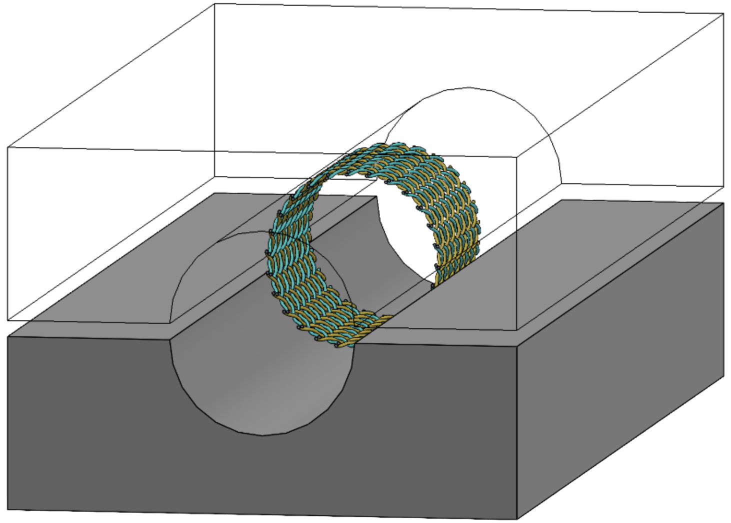
$$dW = F.d\delta$$

$$dW = P\pi DL\frac{dD}{2}$$

→

$$F.d\delta = P\pi DL\frac{dD}{2}$$

P and F perform the equal amount of work



RADIAL PRESSURE	RADIAL FORCE	RADIAL PRESSURE STIFFNESS
$P = \frac{2cF}{DL\tan(\beta)}$	$F_R = \frac{2\pi cF}{\tan(\beta)}$	$K_P = \frac{dP}{dD} = \frac{dP}{d\beta}.\frac{d\beta}{dD}$

$$K_P = \frac{2c}{K_3\sin(\beta)\left(DL\tan(\beta)\right)^2} \times \left[\begin{array}{c} 2DLN.\tan(\beta)\left(\frac{GI_p}{K_3}\left(\frac{2\cos(\beta)}{K_3}\right) - \frac{EI}{K_3}\left(\frac{2\cos(\beta)}{K_3} - \frac{K_2}{\cos^2(\beta)}\right)\right) \\ -F\left(\frac{DL}{\cos^2(\beta)} + K_3\sin(\beta) \times (\pi cD - L.\tan(\beta))\right) \end{array}\right]$$

MECHANICAL PROPERTIES

Shear and bending stress (σ, τ)

Twisting moment

$$\tau = \frac{F.cos(\beta).{}^{D}/_{2}.d/2}{I_p}$$

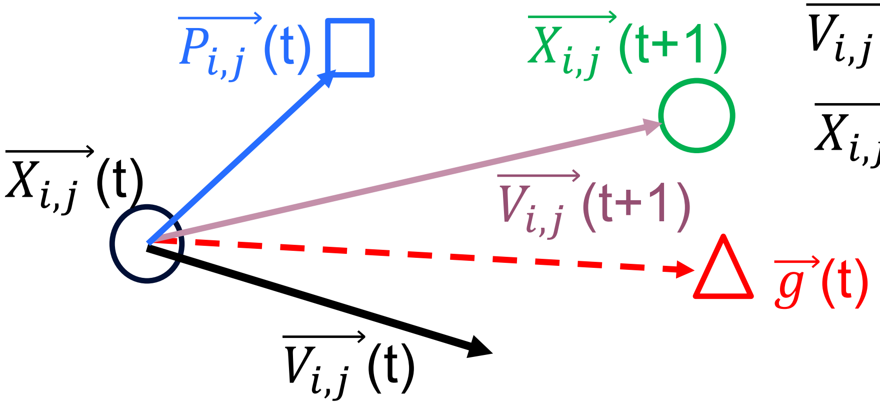
Bending moment

$$\sigma = \frac{Fsin(\beta).{}^{D}/_{2}.d/2}{I}$$

$$\sigma_{eq} = \sqrt{\frac{2\sigma^2 + 6\tau^2}{2}}$$

MULTI OBJECTIVE PARTICLE SWARM OPTIMIZATION

PSO Based on the paradigm of swarm intelligence, introduced by James Kennedy and Russell C. Eberhart in 1995.



$$\overrightarrow{V_{i,j}}(t+1) = w\overrightarrow{V_{i,j}}(t) + r_1 c_1 (\overrightarrow{P_i}(t) - \overrightarrow{X_{i,j}}(t)) + r_2 c_2 (\overrightarrow{g}(t) - \overrightarrow{X_{i,j}}(t))$$

$$\overrightarrow{X_{i,j}}(t+1) = \overrightarrow{X_{i,j}}(t) + \overrightarrow{V_{i,j}}(t+1)$$

w = Inertia Weight

c_1 = Personal Learning Coefficient

c_2 = global Learning Coefficient

MOPSO Developed by Carlos et.al in 2004

- Like PSO particles are sharing info. & moving towards global best particles and their own personal best memories.
- Unlike PSO there is more than one criterion to determine and define the best global.

Non-dominated particles ⇨ Repository

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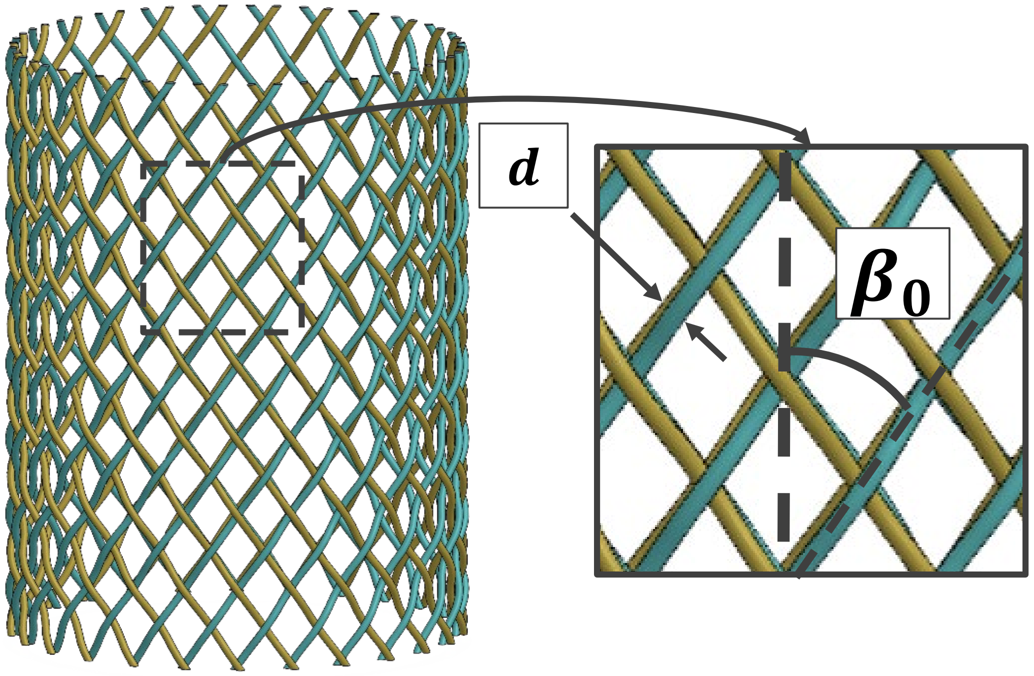
MULTI OBJECTIVE PARTICLE SWARM OPTIMIZATION



DESIGN VARIABLES

$$N = \textit{Number of wires}$$
$$\beta_0 = \textit{Initial pitch angle}$$
$$d = \textit{Diameter of the wire}$$

$$V = N.\frac{L_0}{\sin\beta_0}.\pi d^2$$

COST FUNCTIONS

$$\begin{cases} \textbf{Minimize} \text{ the maximum } \textbf{stent length} \\ \textbf{Maximize} \text{ the } \textbf{radial Force} \text{ exerted on the veins} \\ \textbf{Maximize} \text{ the radial } \textbf{stiffness} \end{cases}$$

CONSTRAINTS

$$V_{Optimized} \leq V_{Jedwab}$$
$$\sigma_{eq} < \textit{yield strength}$$
$$\beta_{min} > \arctan\left(\frac{dN}{\pi D}\right)$$

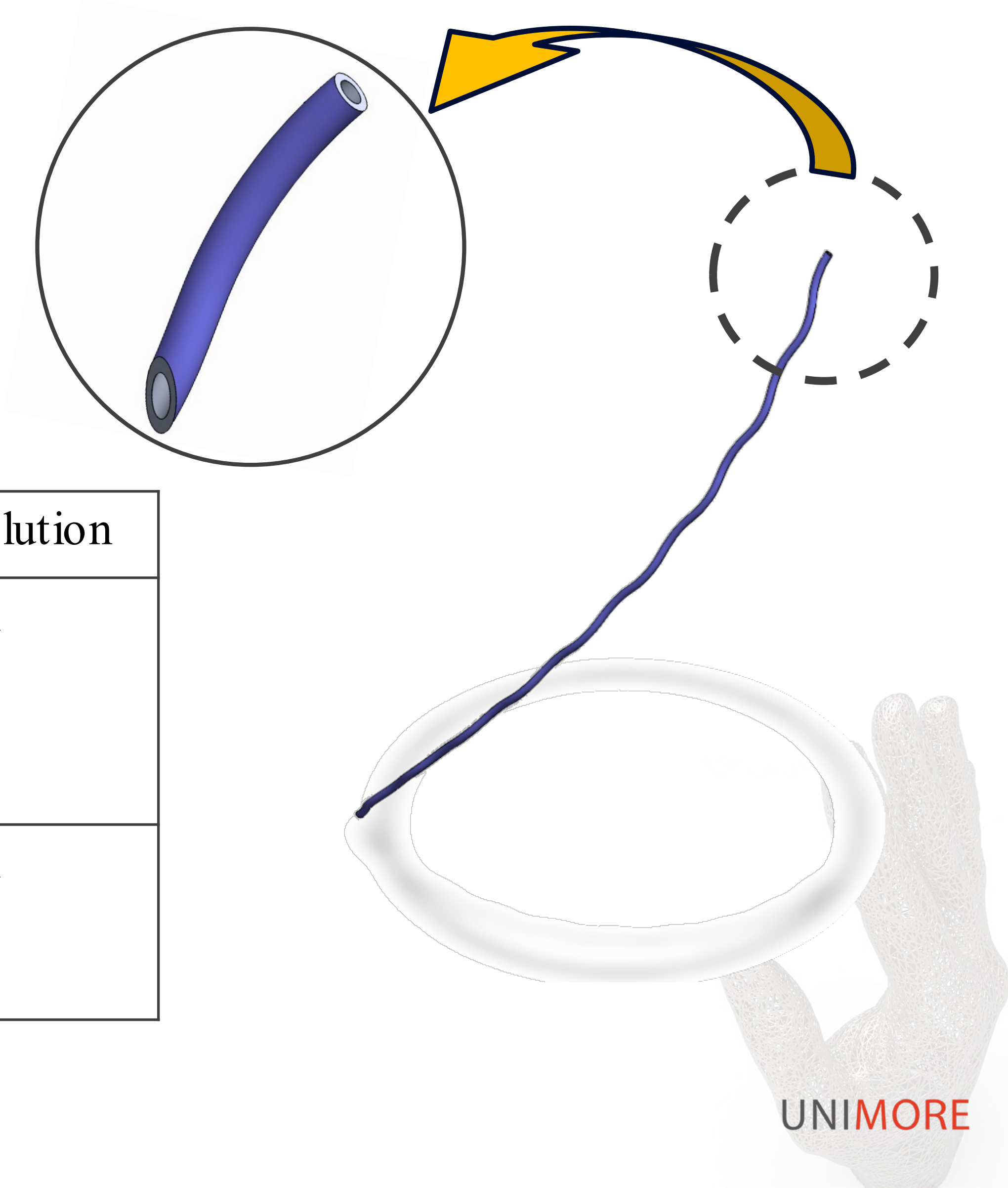
USE OF AM TO GET HOLLOW / LIGHTER STRUCTURE

t = Thickness

$$d_{in} = 2(\frac{d}{2} - t)$$

$$I_P = \frac{\pi}{32}(d^4 - d_{in}^4)$$

$$I = \frac{\pi}{32}(d^4 - d_{in}^4)$$

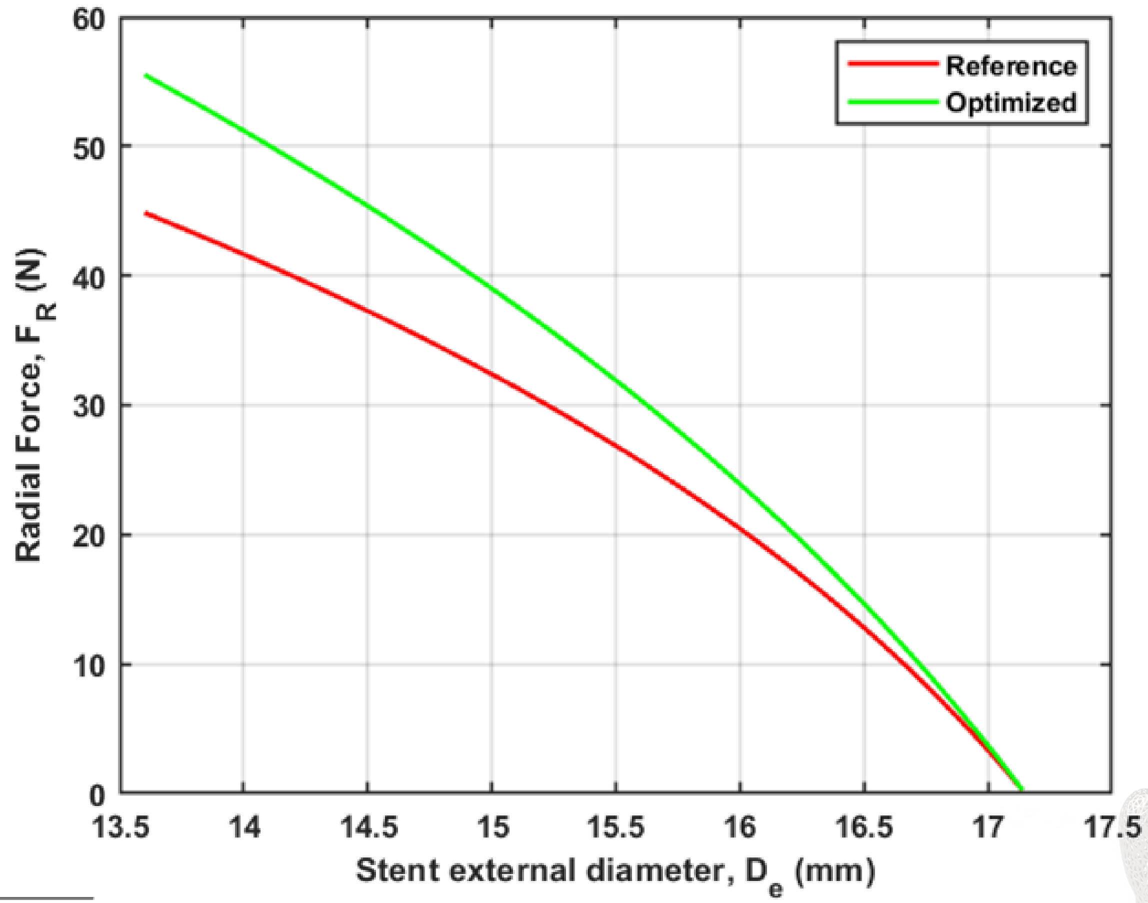


Method	Common material	Resolution
SLM	Stainless steels, aluminium (Al), copper (Cu), iron (Fe), cobalt (Co)-chrome (CR), Ti, Ni-based alloy, and a mixture of different types of particles (Fe, Ni, Cu, and Fe3P)	20 µm
DED	Steel alloys, stainless steel, tool steel, Al, bronze, Co-Cr, (Fe, Ni)-TiC composites and Ti ,	20 µm

RESULTS: RADIAL FORCE

Parameter	value
Initial average stent diameter D_0 (mm)	16.71
Wire diameter d (mm)	0.22
Number of wires N	24
Volume of the stent (mm^3)	673
Initial pitch angle β_0 (°)	28.3
Initial stent length $L_0(mm)$	87.5
Young's modulus E (MNm^{-2})	206000
Yield stress $S_y(MNm^{-2})$	2500

Design	N	d	β_0	$Volume$
Opt.1	18	0.266	31.54	670



$D_0\ (fully\ deployed) \rightarrow 0.8D_0$

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RESULTS: RADIAL PRESSURE STIFFNESS

Parameter	value
Initial average stent diameter D_0 (mm)	16.71
Wire diameter d (mm)	0.22
Number of wires N	24
Volume of the stent (mm^3)	673
Initial pitch angle β_0 (°)	28.3
Initial stent length $L_0(mm)$	87.5
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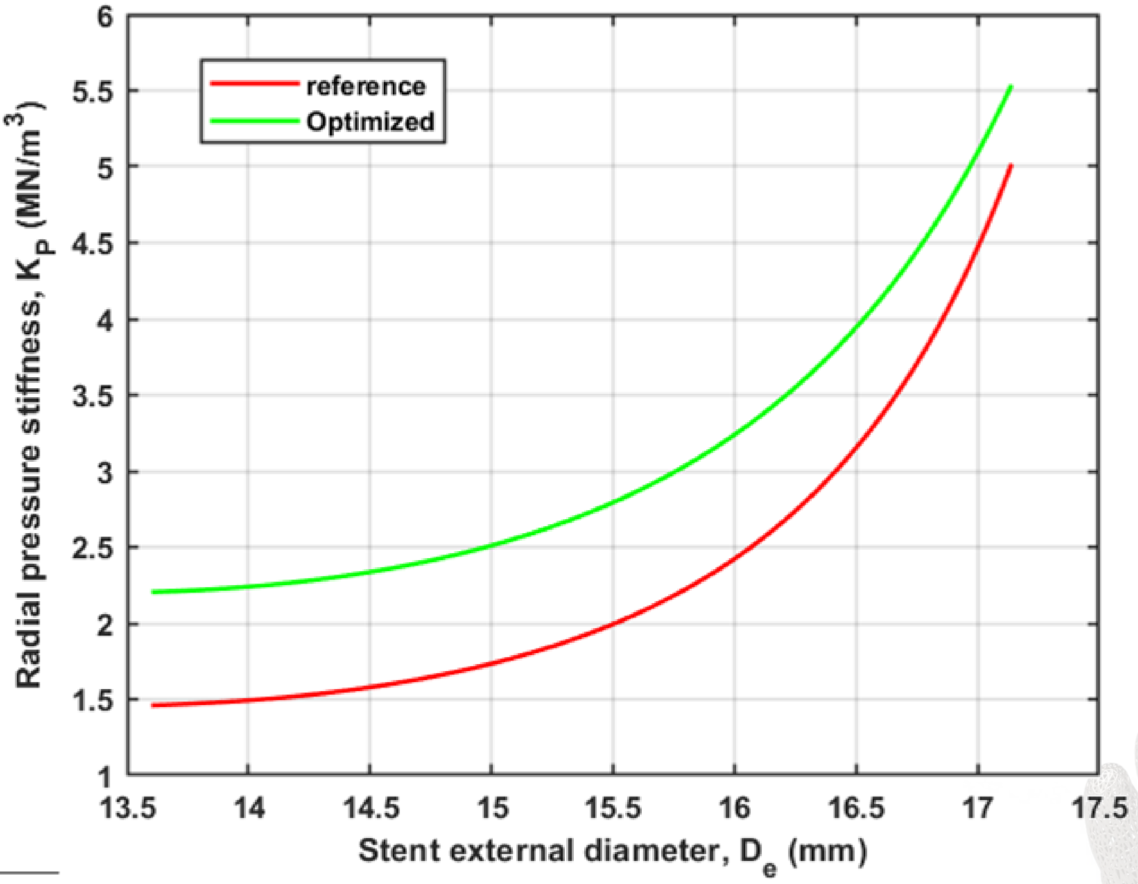

$$D_0\ (fully\ deployed) \rightarrow 0.8D_0$$

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RESULTS: STENT LENGTH

Parameter	value
Initial average stent diameter D_0 (mm)	16.71
Wire diameter d (mm)	0.22
Number of wires N	24
Volume of the stent (mm^3)	673
Initial pitch angle β_0 (°)	28.3
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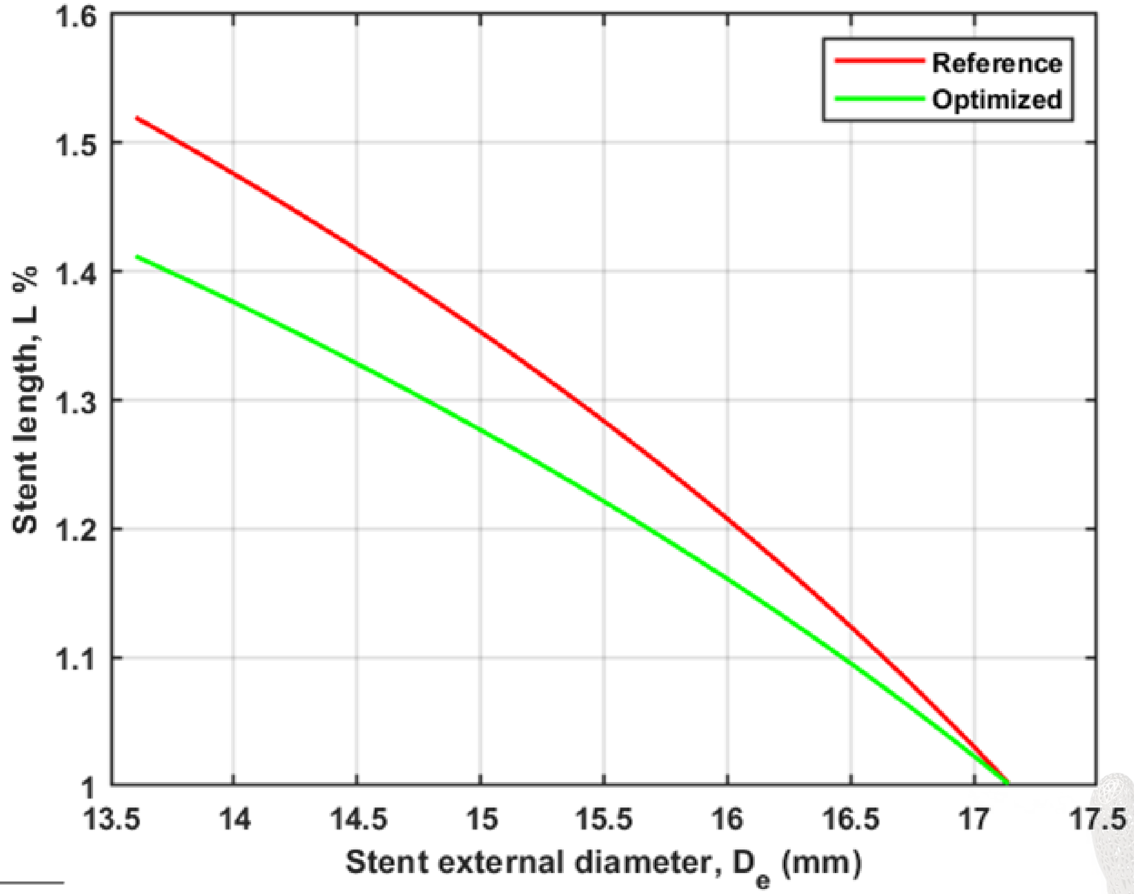
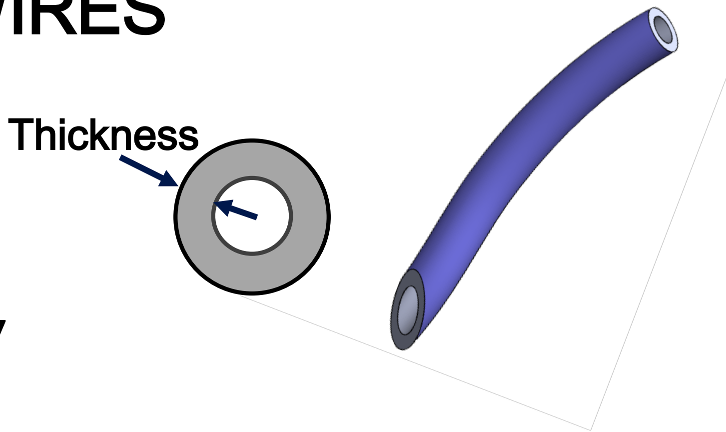


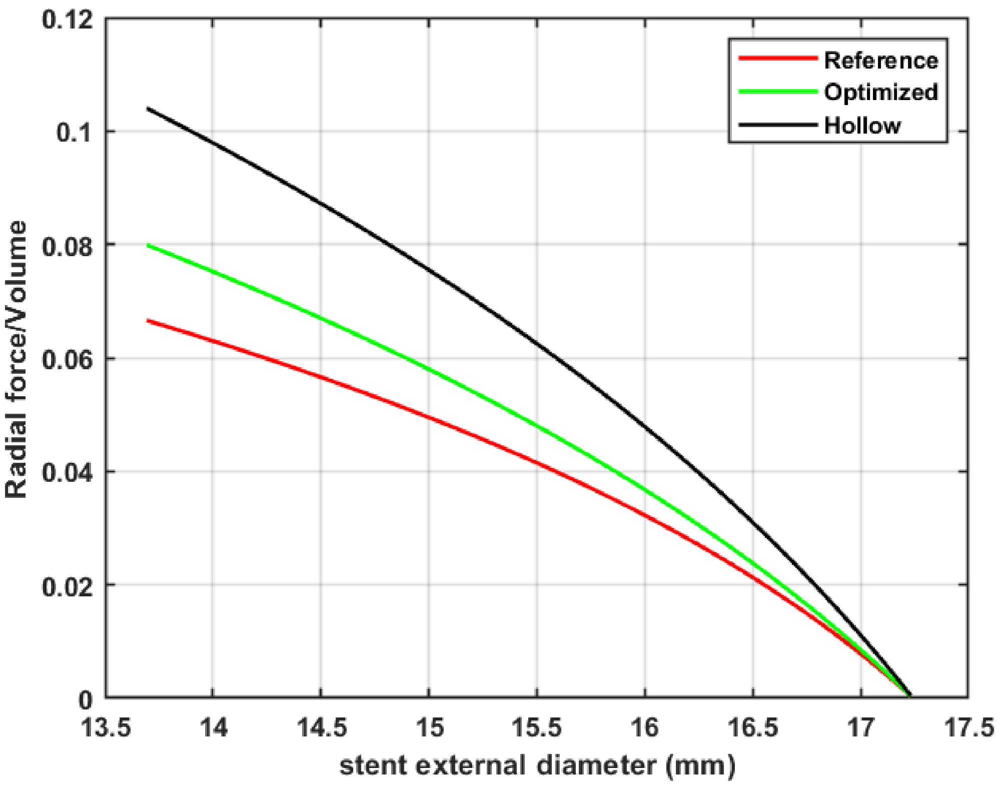
$D_0\ (fully\ deployed) \rightarrow 0.8D_0$

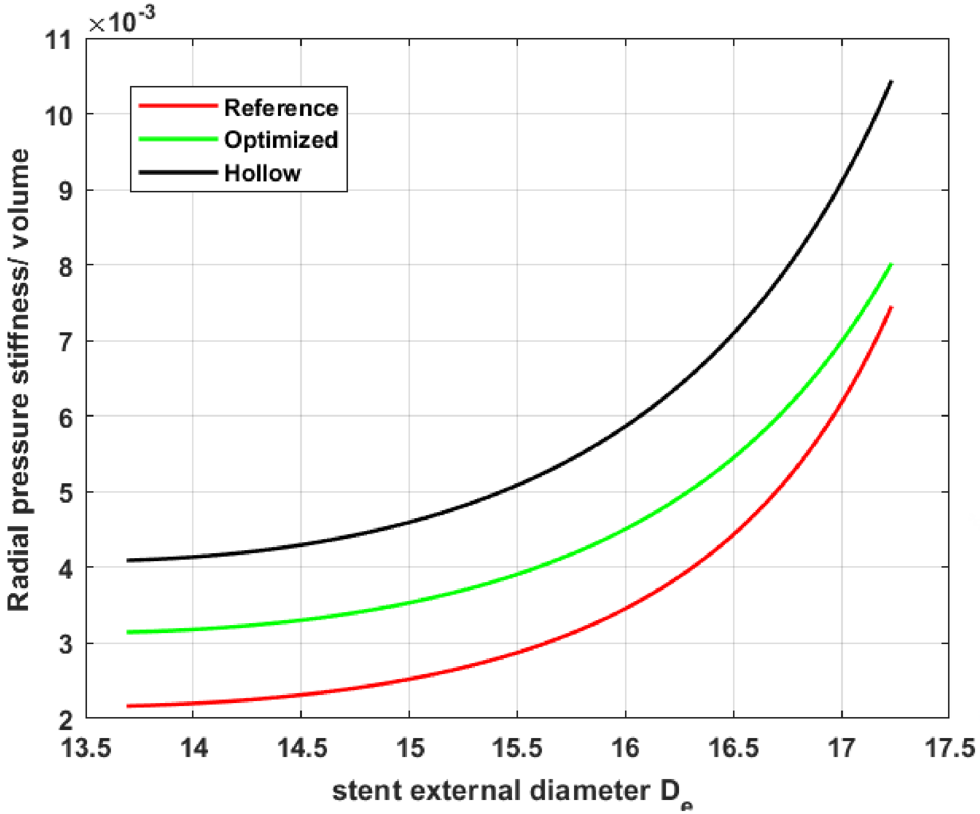
AM TECHNOLOGY : 3D PRINTED HOLLOW WIRES

$$\text{Volume Reduction Ratio (VRR)} = \frac{initial\ volume - final\ volume}{initial\ volume} \times 100$$



Thickness $= 60\ \mu m$ Final volume $= 468\ mm^3$ → $\boldsymbol{VRR = 30.17}$





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CONCLUSION & FUTURE DEVELPMENT

1. Optimize the performance of an open-ended braided stent
2. Analytical approach + MOPSO optimization
3. Specific radial force, Fr, specific radial pressure stiffness, Kp, are optimized
4. Fr and Kp increased especially for lower diameters
5. The stent's maximum length is reduced from 1.51% to 1.41%.
6. A 3D-printed hollow structure is envisioned
7. According to the optimization stent's weight is lowered by 30%.
8. Future steps: extend the optimization to superelastic NiTi