BIOMEDICAL ENGINEERING DESIGN

TU Delft

WB2308

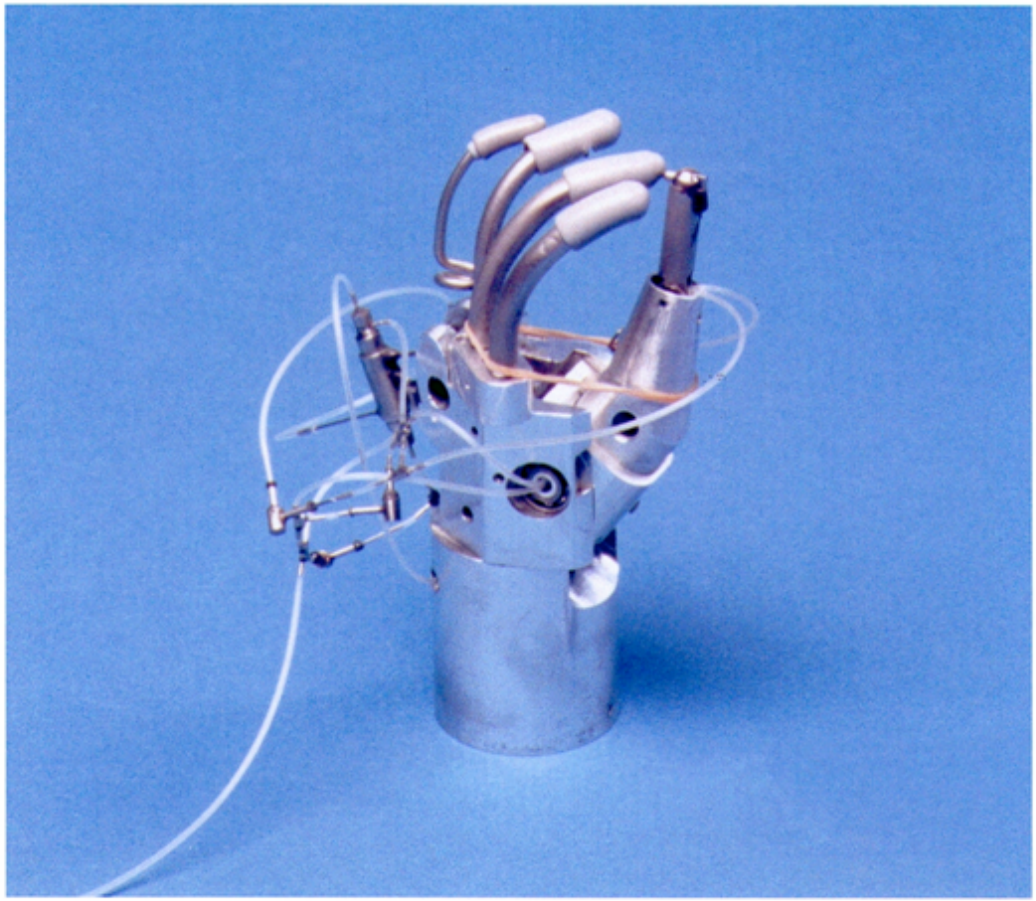
LECTURE STRUCTURE

1. INTRODUCTION
   CLINICALLY DRIVEN PROBLEM ANALYSIS ASSIGNMENT
2. BASIC REQUIREMENTS: REHABILITATION
3. BASIC REQUIREMENTS: ORTHOPAEDICS
4. PROBLEM ANALYSIS: STUDENT PRESENTATIONS
5. DESIGN ENGINEERING: THE CREATIVE PROCESS
6. DESIGN ENGINEERING PRINCIPLES
7. EXAMPLES: **REHABILITATION**
   ORTHOPAEDICS

A SIZZLING HAND PROSTHESIS

ON THE DESIGN AND DEVELOPMENT OF A PNEUMATICALLY POWERED HAND PROSTHESIS FOR CHILDREN

DICK H. PLETTENBURG



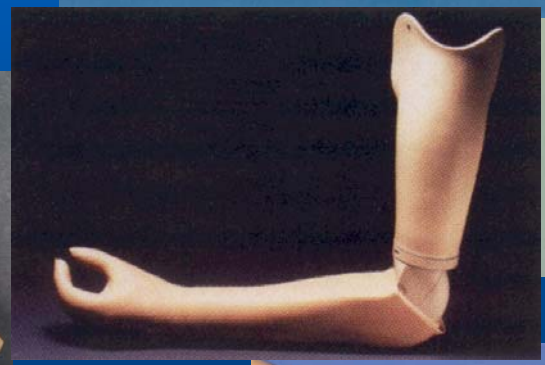
Presentation overview

- Background
- History of pneumatic actuation
- Project goals
- Methods
- Results
- Concluding remarks

Background

- **Many different types of prostheses available**

Background



WILMER, Netherlands
Hosmer Dorrance, USA
Otto Bock Healthcare GmbH
Motion Control, USA

Background

- Many different types of prostheses available
- But all fail to comply with the basic requirements

Background

RSL-Steeper, UK

Centri AG, Sweden

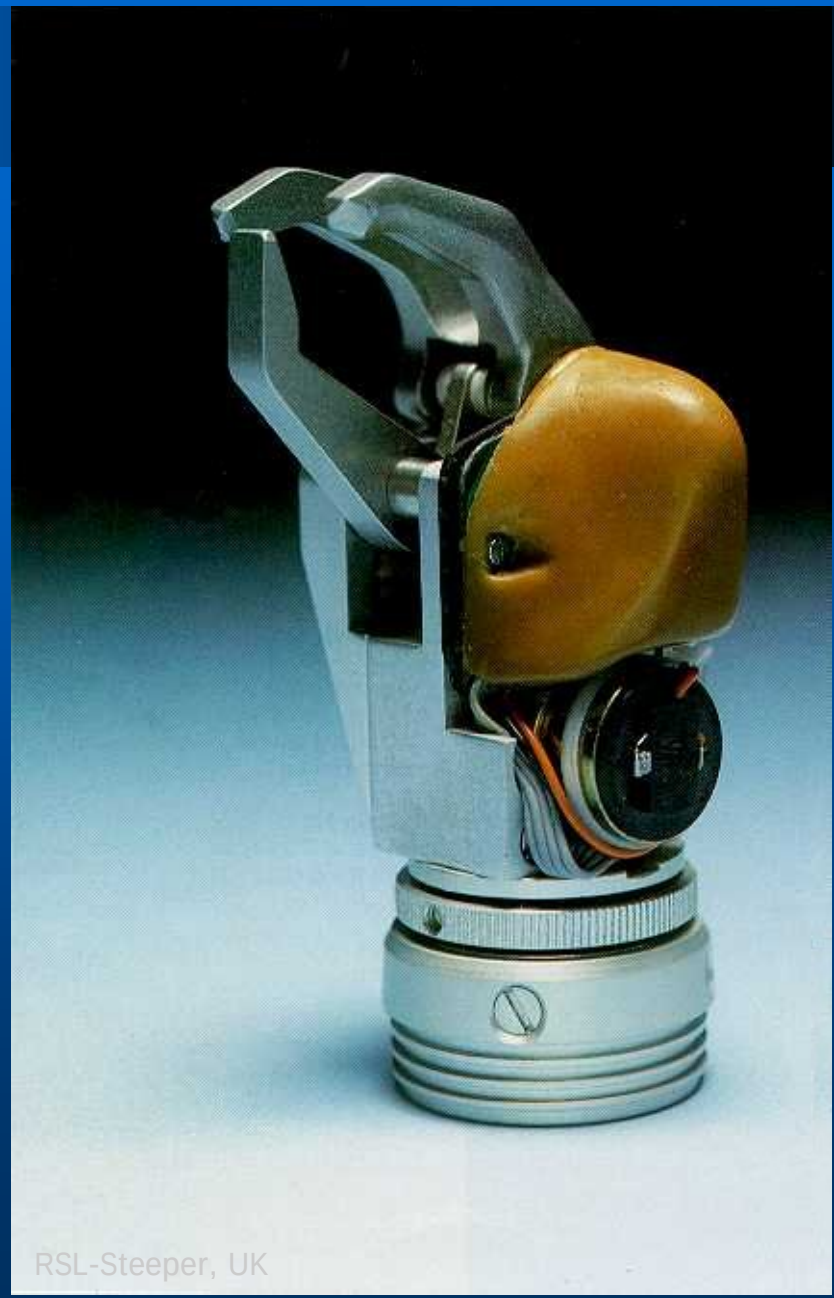
Otto Bock Healthcare GmbH

VASI Inc., Canada

Background

Disadvantages electric actuation:

- **Mass**
- **Speed**
- **Vulnerable**
- **Size**



Background

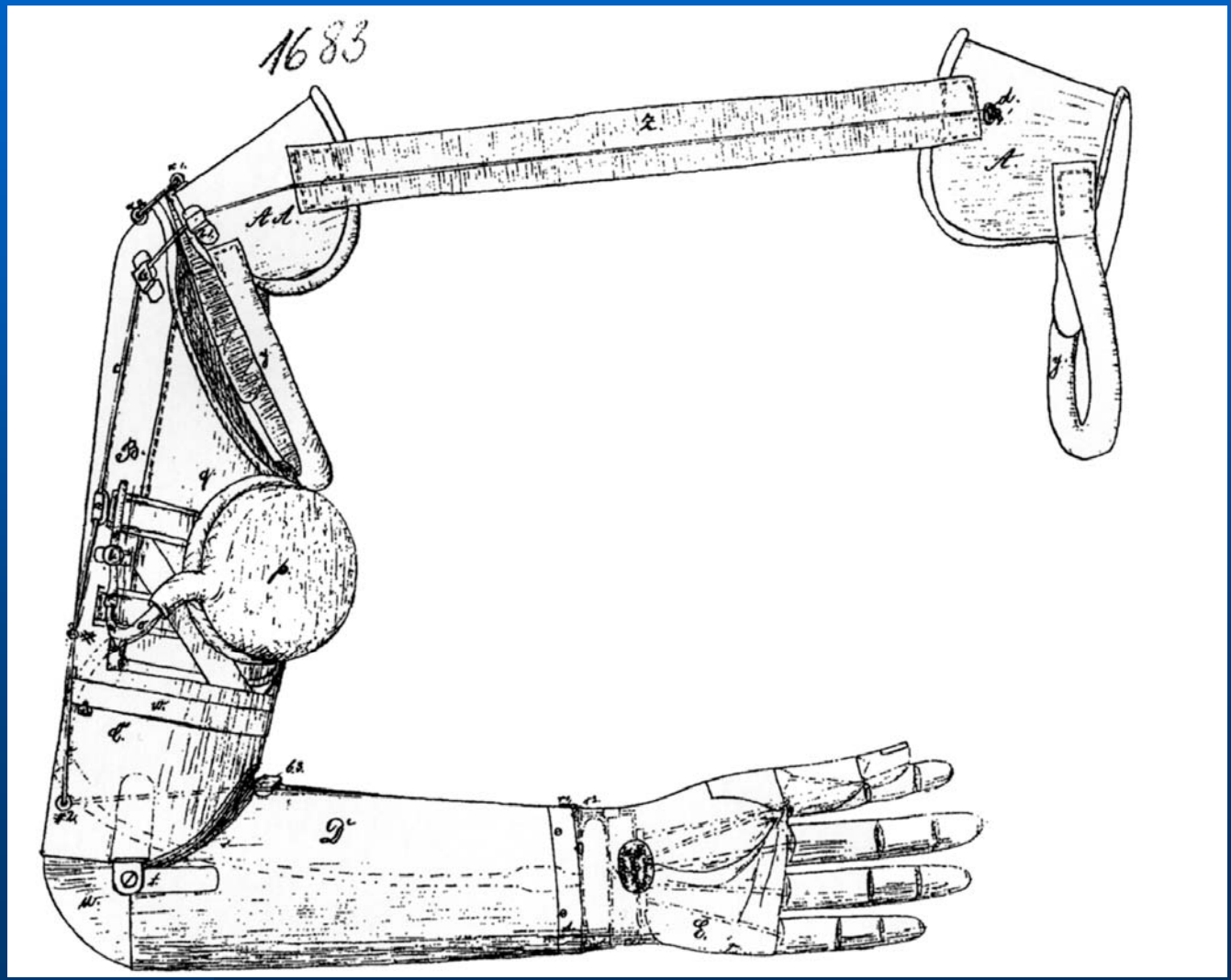
Pneumatic actuation:

- **Light**
- **Fast**
- **Reliable**
- **Small**

History of pneumatic actuation

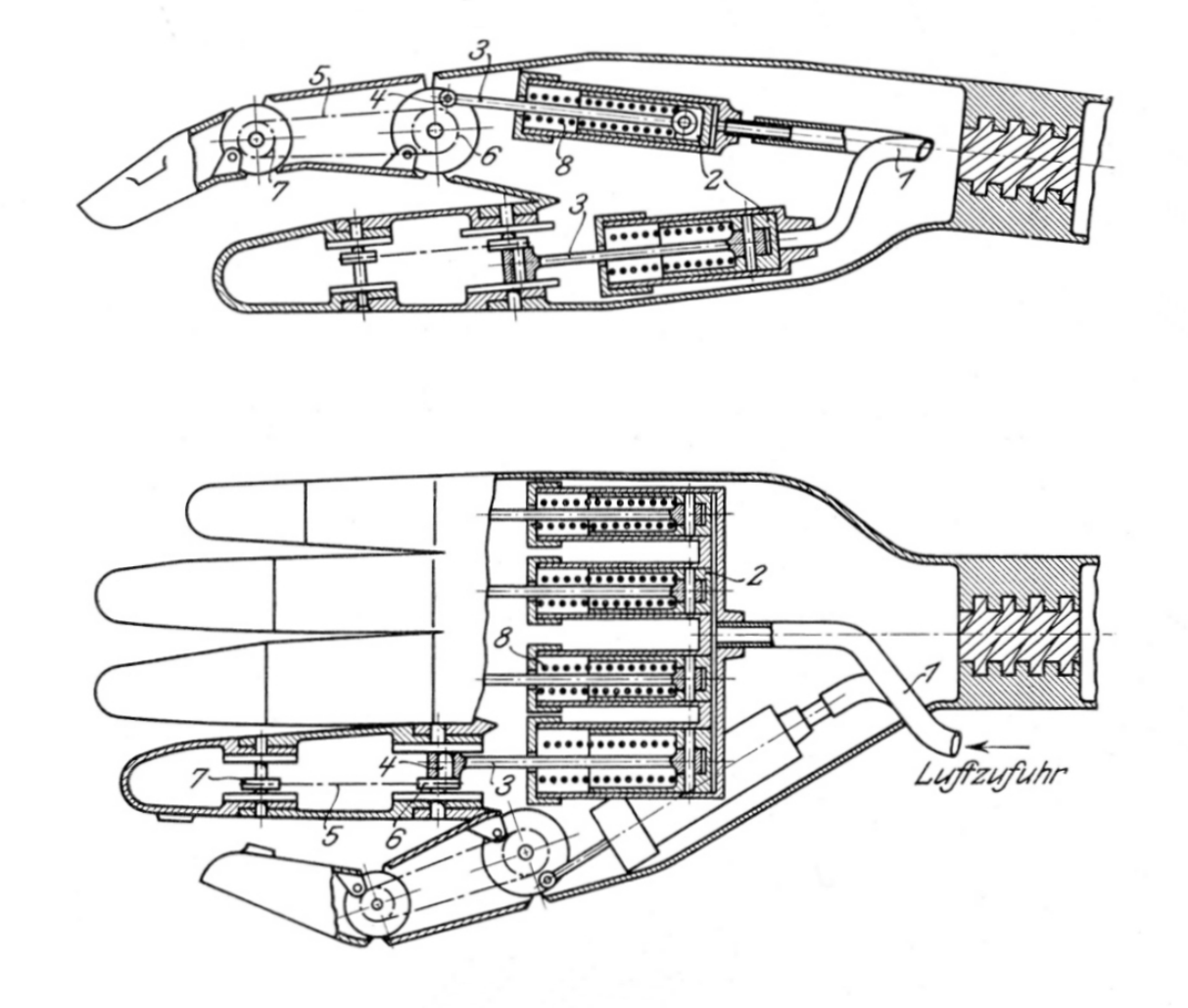
- **Dates back to 1877!**

History of pneumatic actuation



Dalish, 1877

History of pneumatic actuation



Anonymous, ±1919

History of pneumatic actuation

- **Dates back to 1877!**
- **Boosted in mid 20th century: Thalidomide!**

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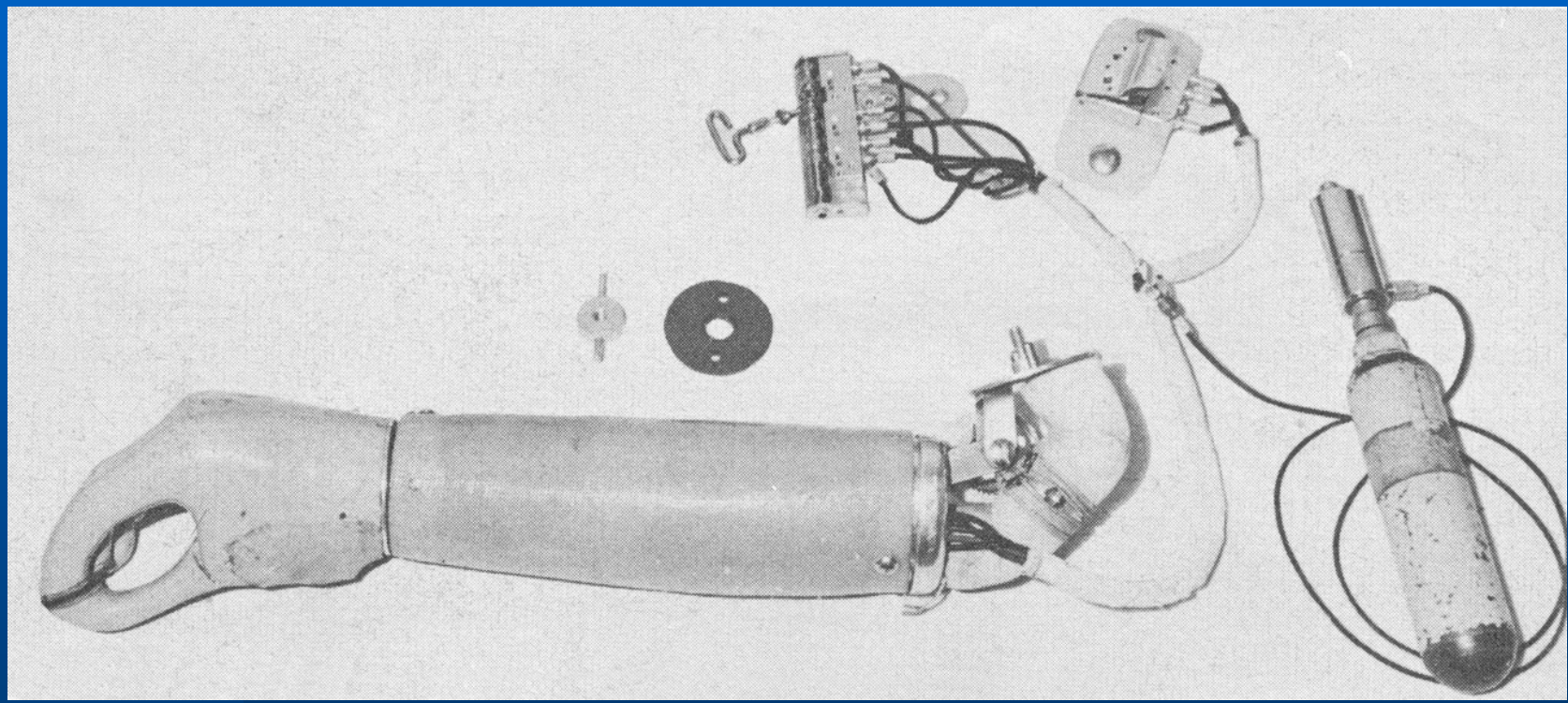
History of pneumatic actuation

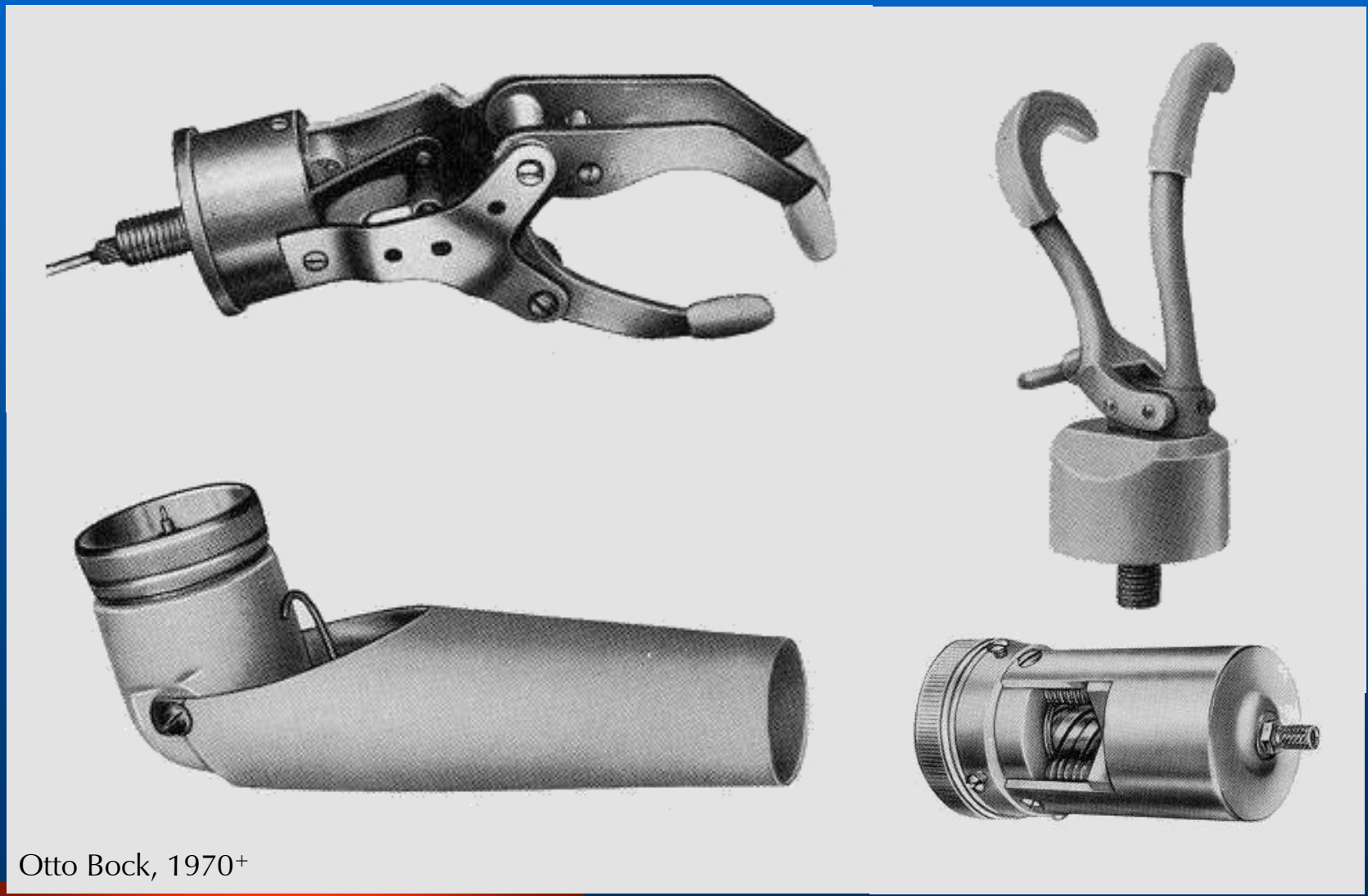


Heidelberg, 1949+

History of pneumatic actuation

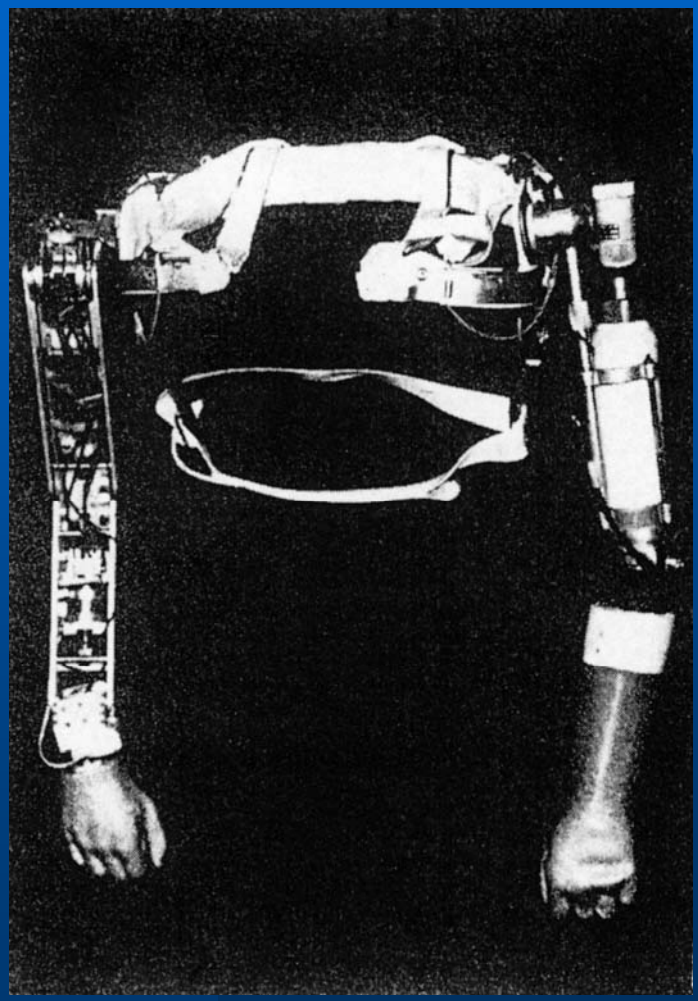
Steeper, 1964

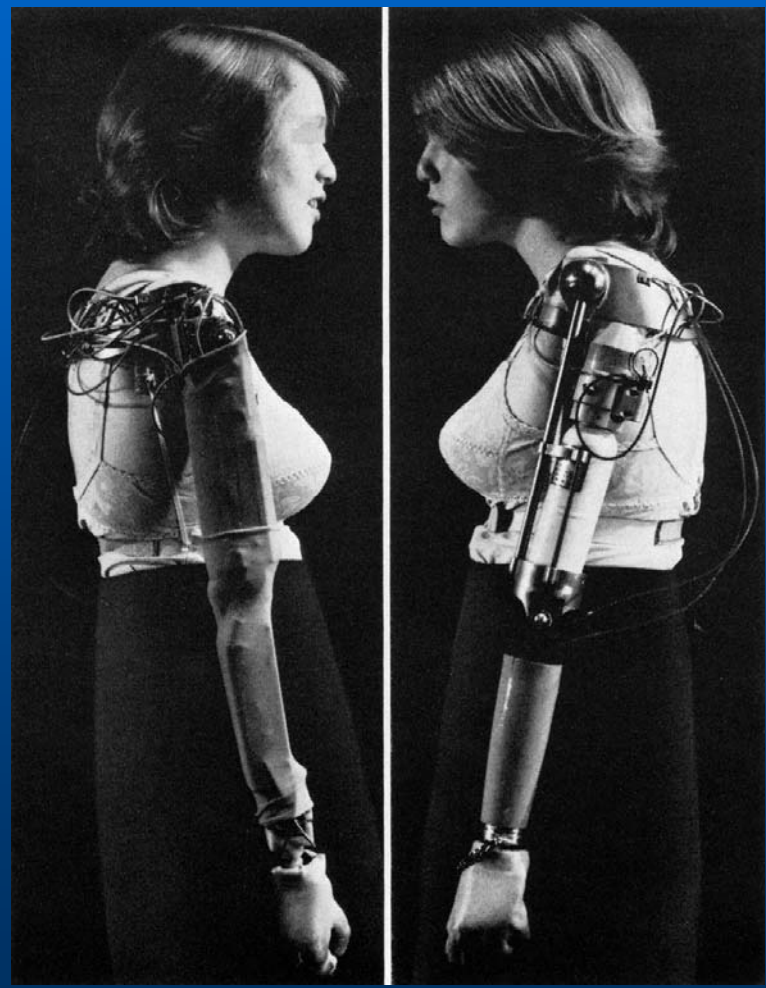
History of pneumatic actuation



Otto Bock, 1970+

History of pneumatic actuation





Edinburgh, 1963 - 1977

History of pneumatic actuation

- **Never successful:**
  - **Gas containers**
  - **Gas consumption**
  - **Overall mass**

History of pneumatic actuation

History of pneumatic actuation

Project goals

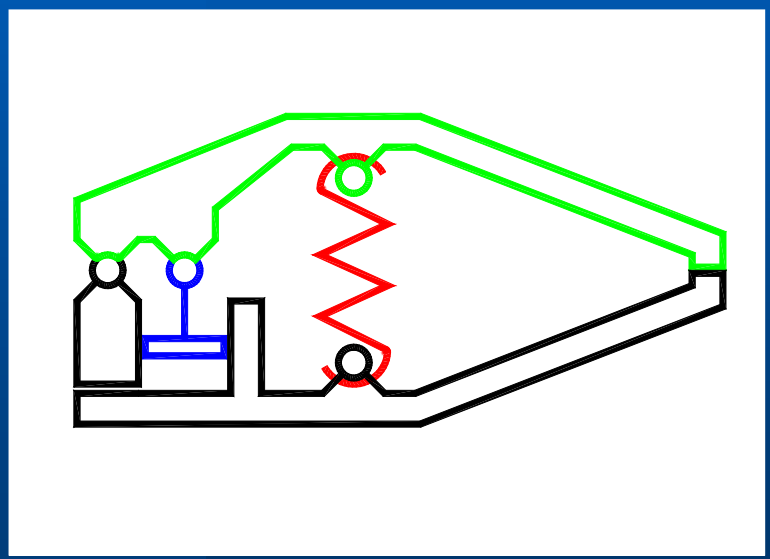
- **Re-assessment pneumatic actuation:**
  - **Light?**
  - **Fast?**
  - **Reliable?**
  - **Small?**

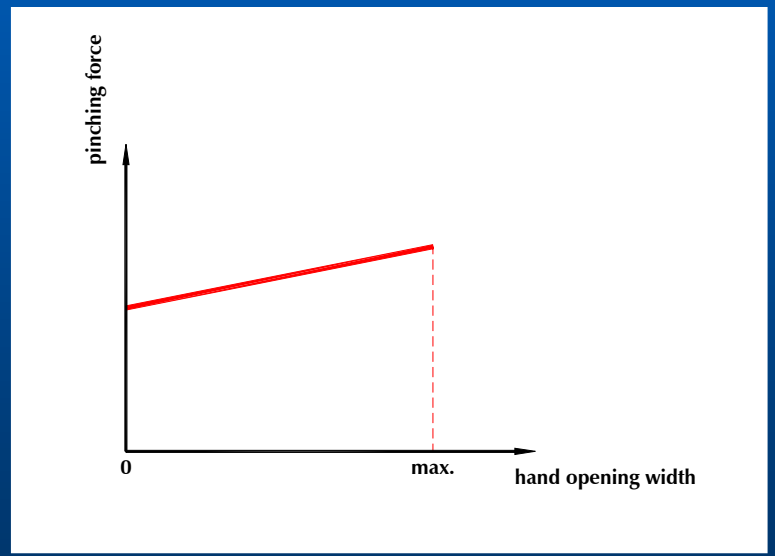
Method

- Minimize gas consumption by
  - System choice
  - Reduction of friction losses
  - Reduction of dead space
  - Supply pressure
- Prototypes

Method – system choice

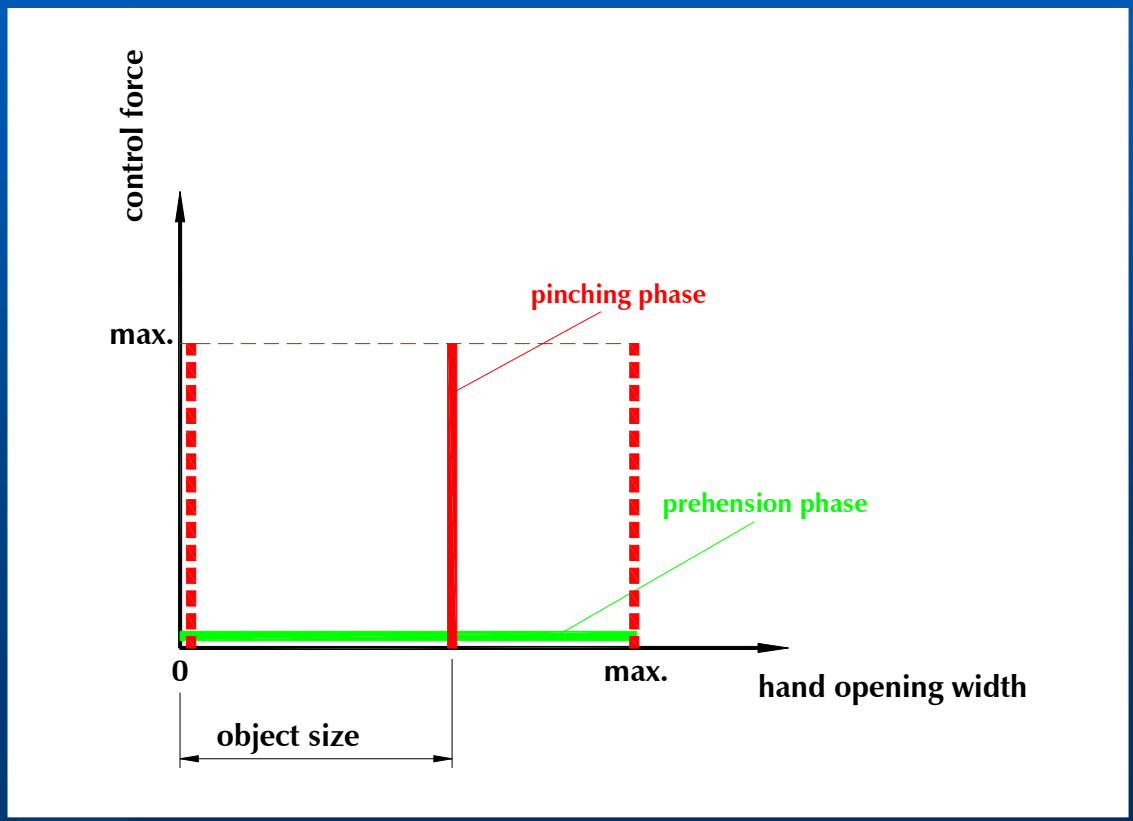
- **'Standard' operation**





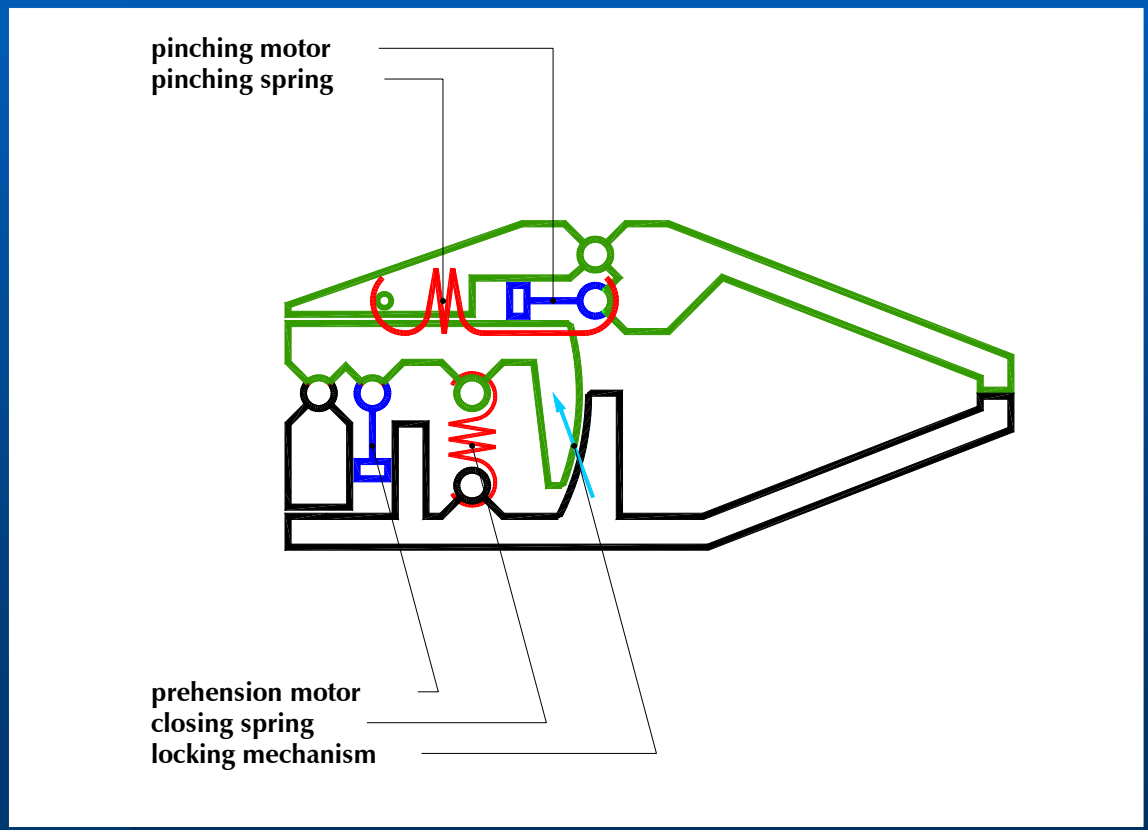
Method – system choice

- **'Bi-phasic' operation**



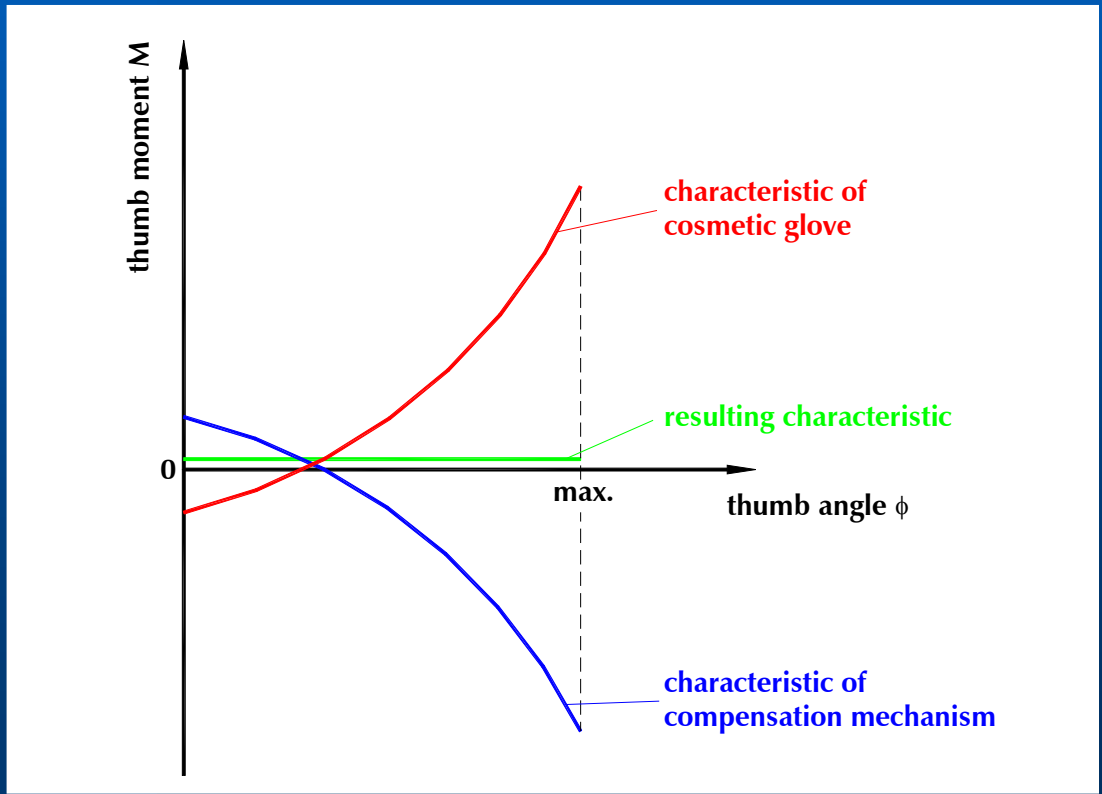
Method – system choice

- **'Bi-phasic' operation**

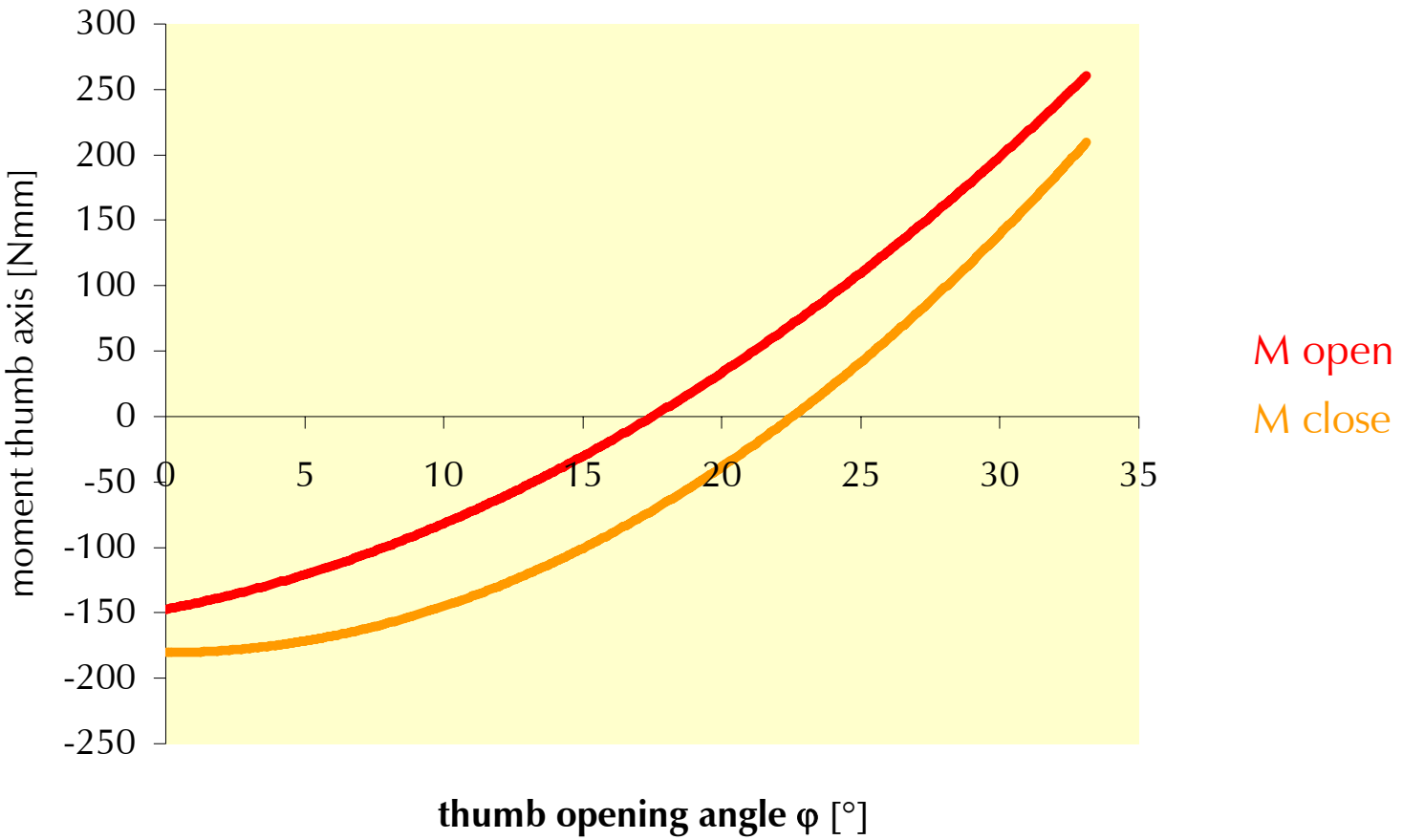


Method – system choice

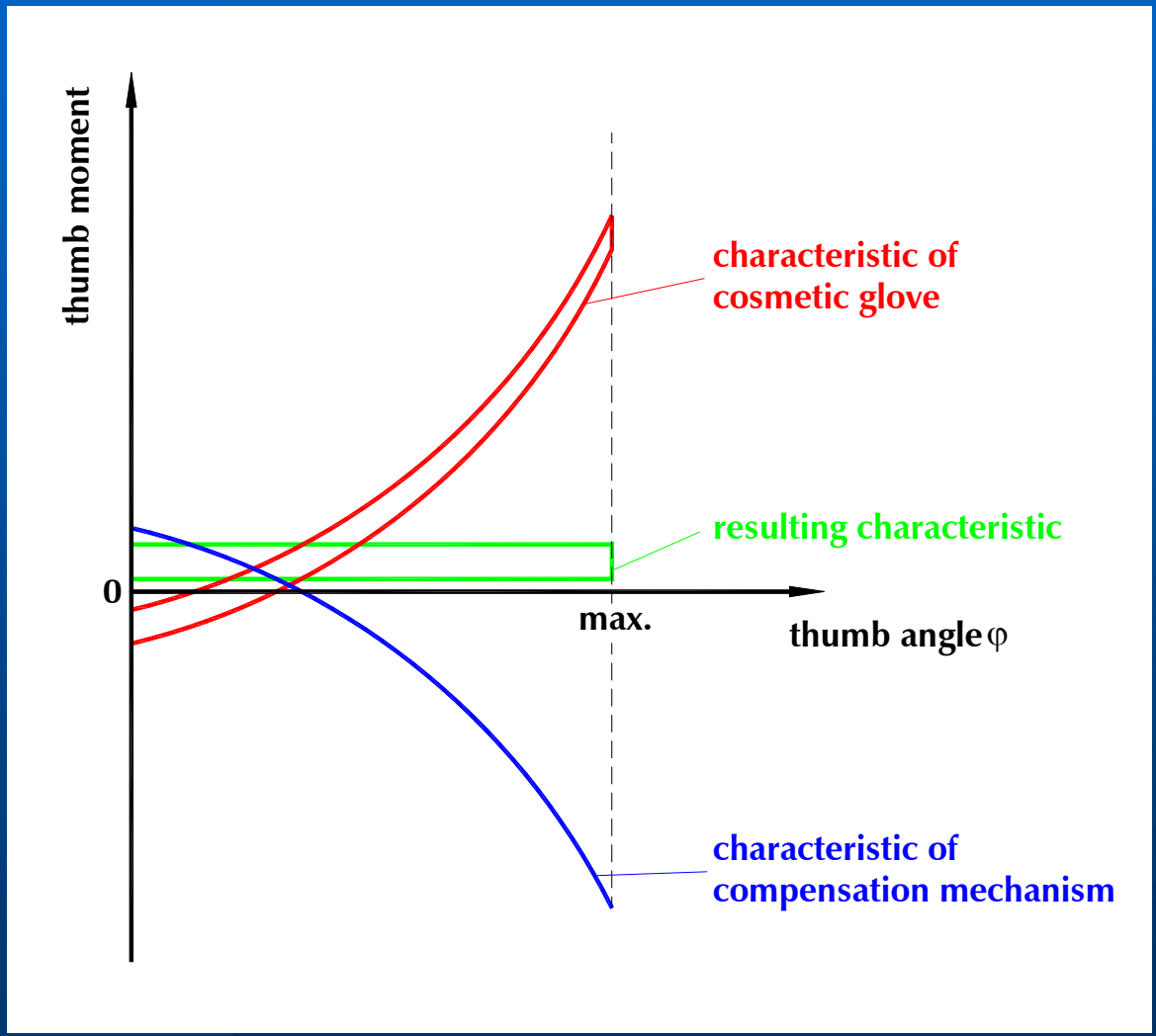
- **Glove compensation**



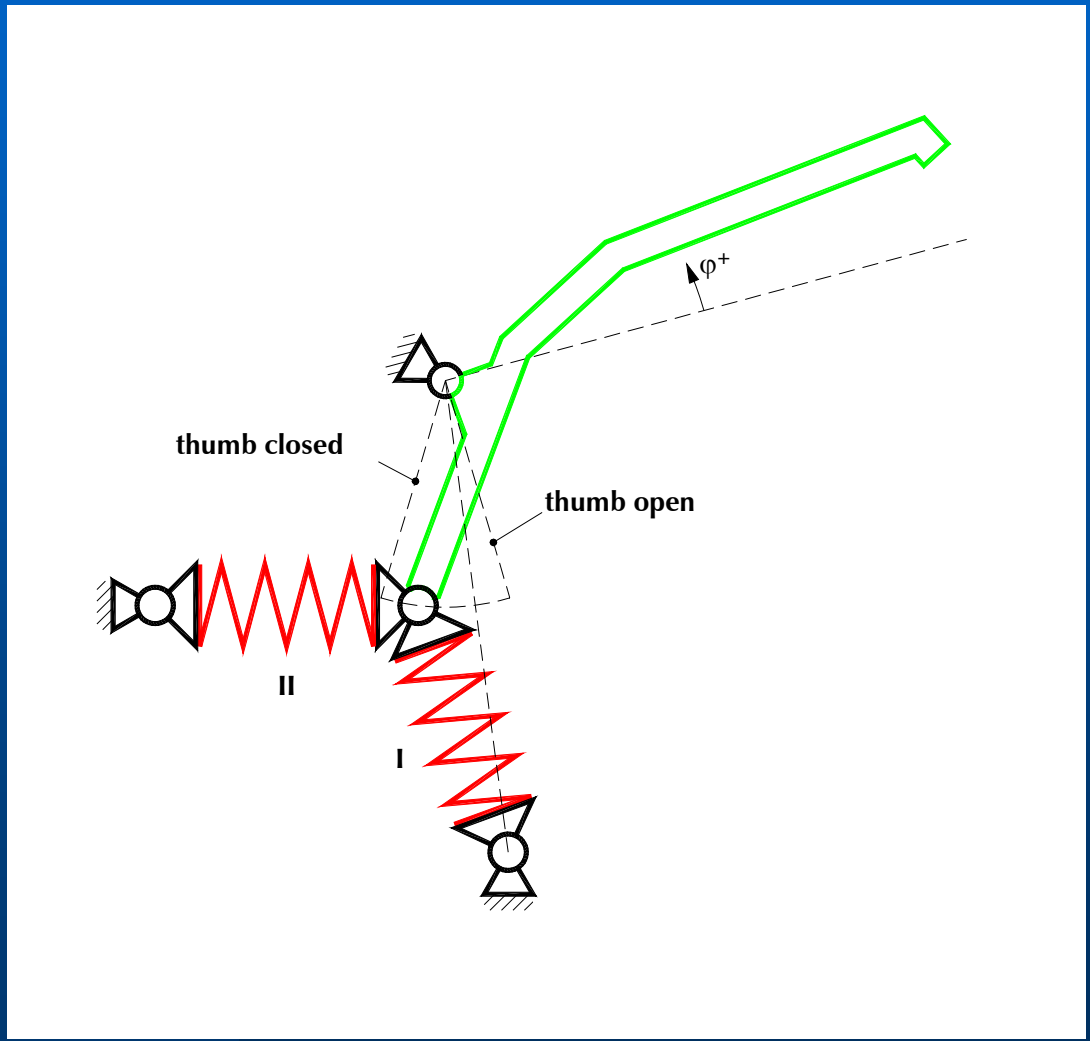
Method – system choice



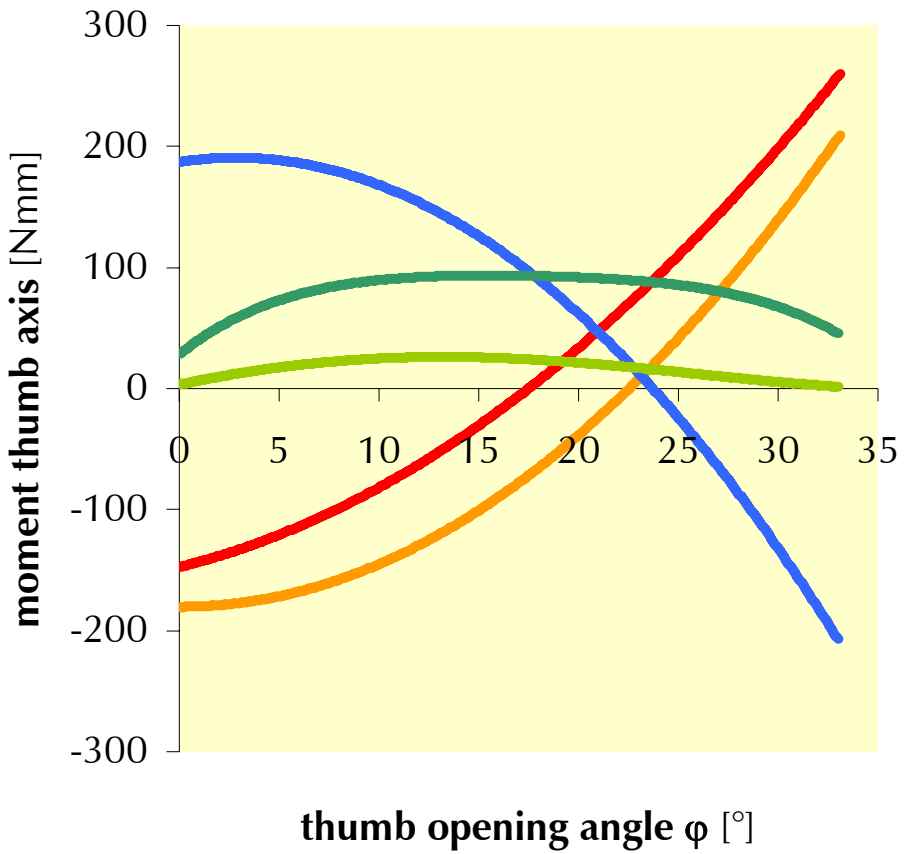
Method – system choice



Method – system choice



Method – system choice



M open

M close

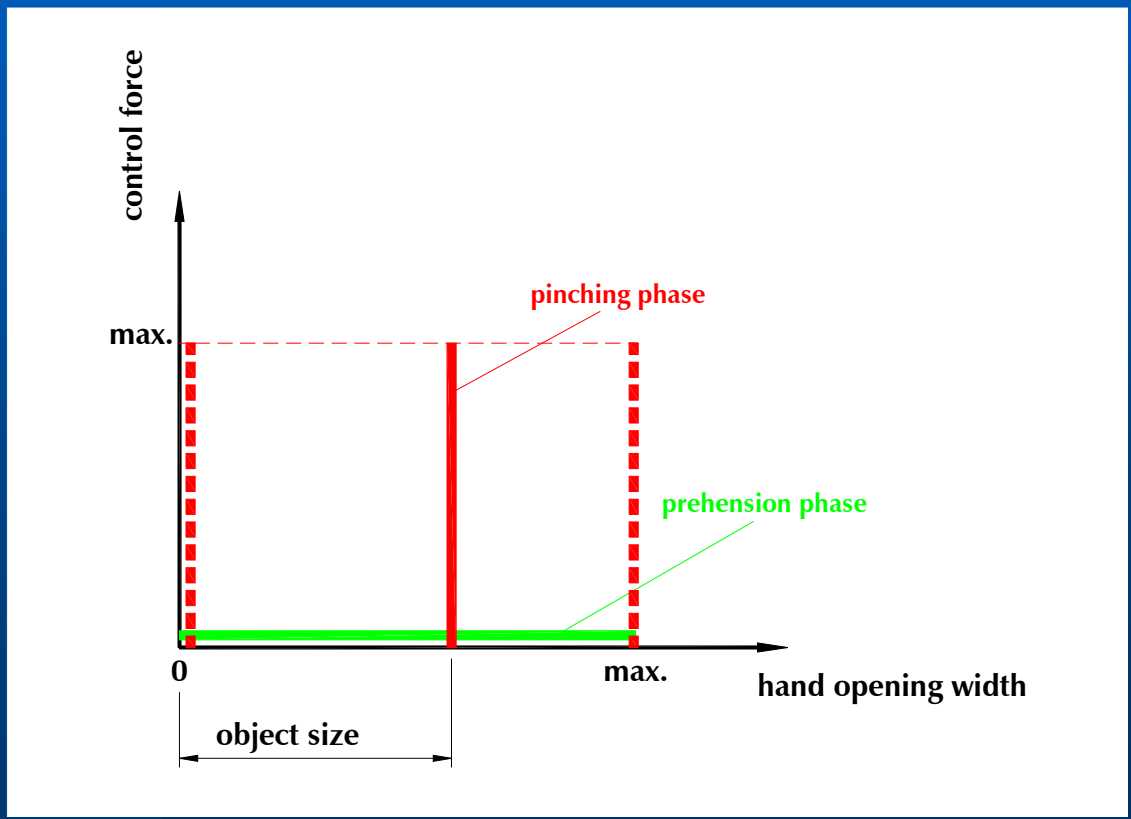
compensation moment

remaining closing moment

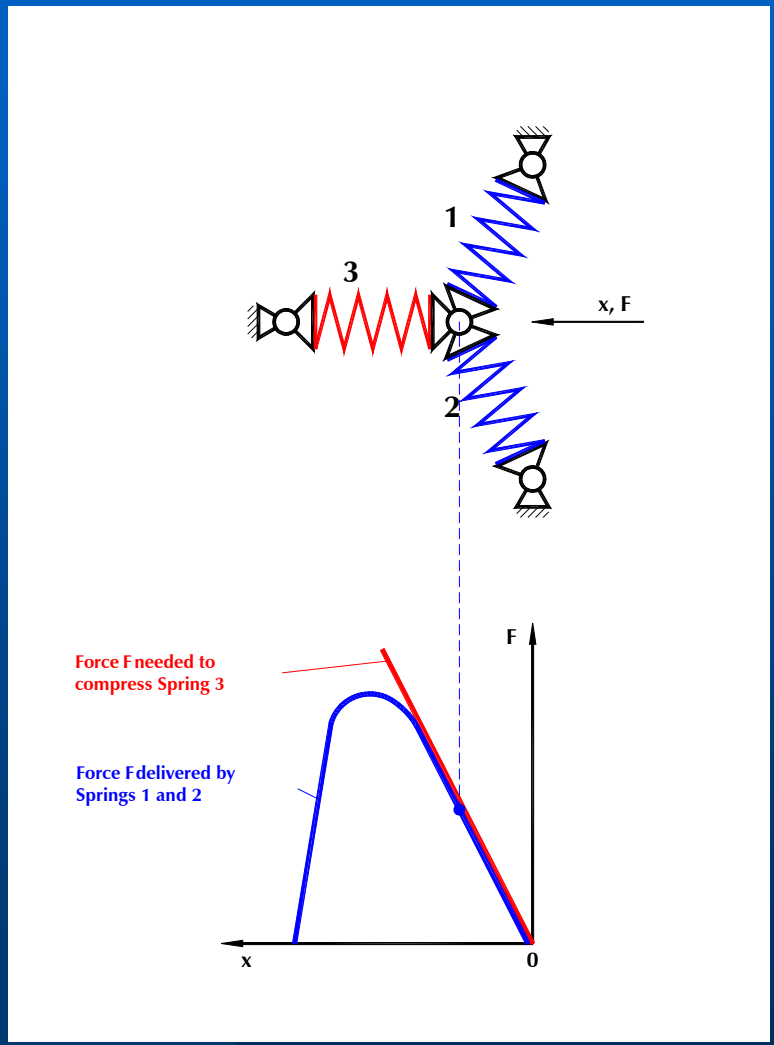
remaining opening moment

Method – system choice

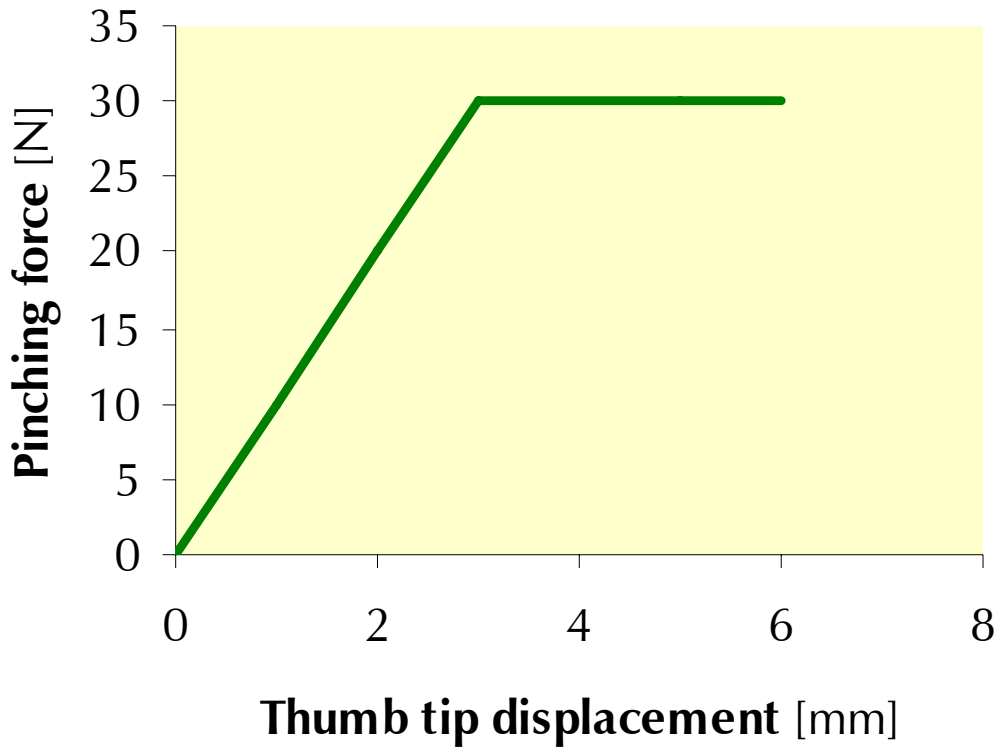
- **Pinching Phase Mechanism**



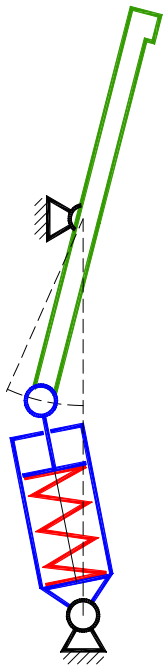
Method – system choice

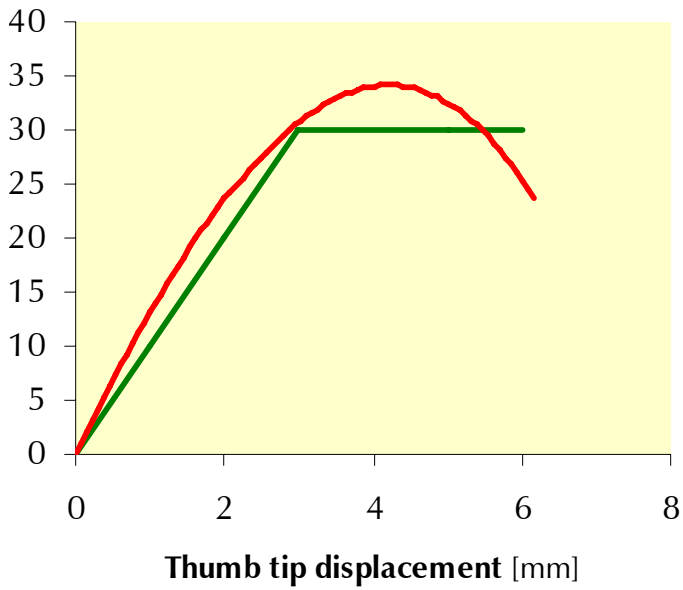


Method – system choice



Method – system choice



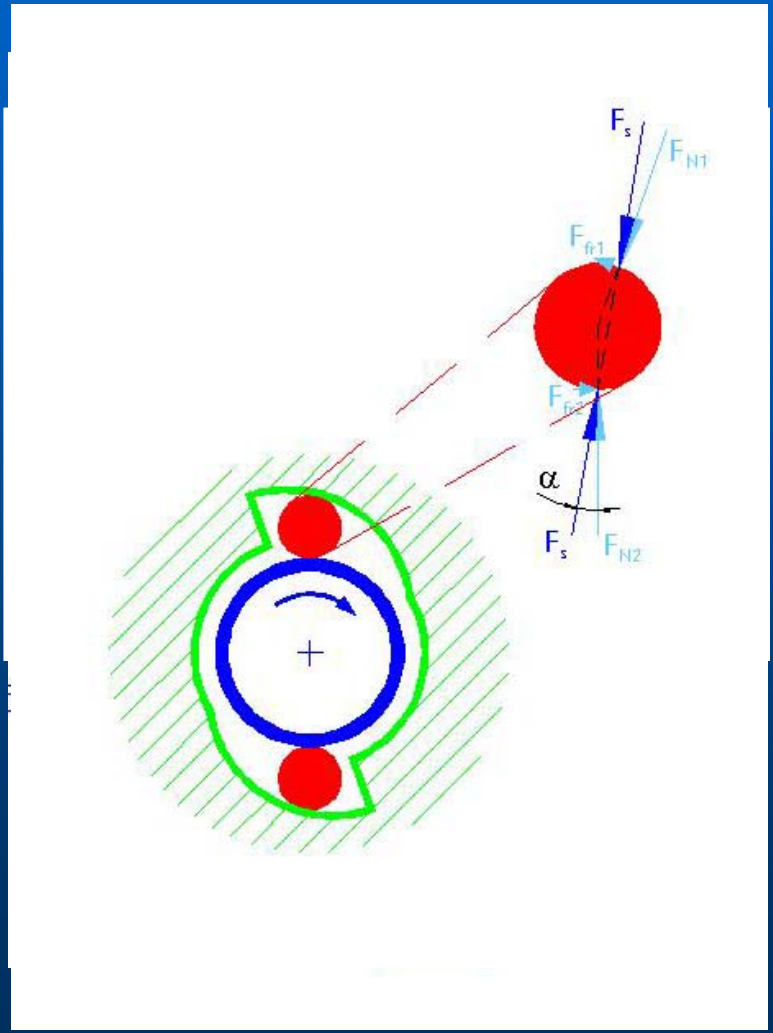


desired pinching force

resulting pinching force

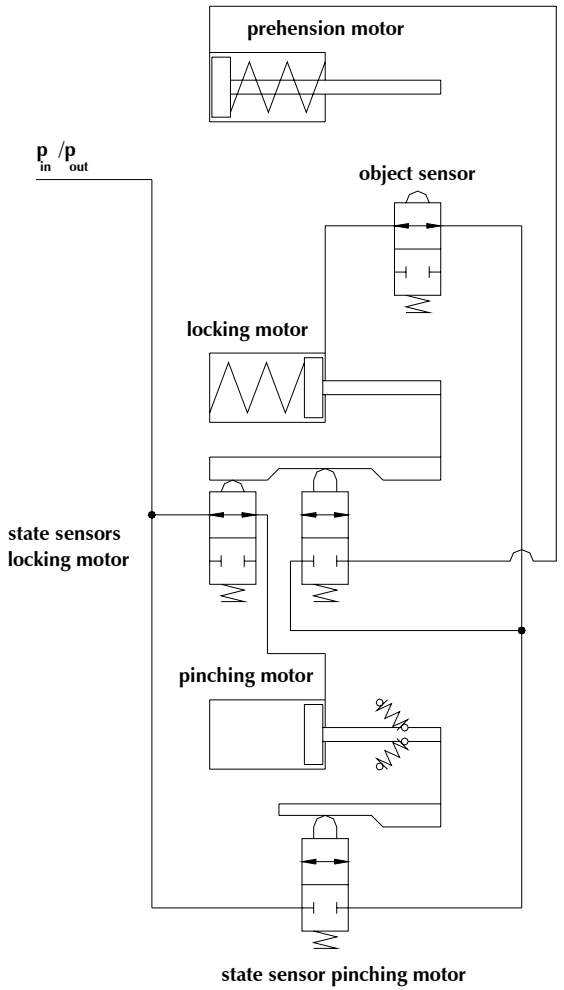
Method – system choice

- **Locking mechanism:**
  - **Continuously adjustable**
  - **Friction free**
  - **Rigid**
  - **Fast switching**
  - **Low energy**
  - **No backlash**
  - **Quiet**
  - **Overload protection**

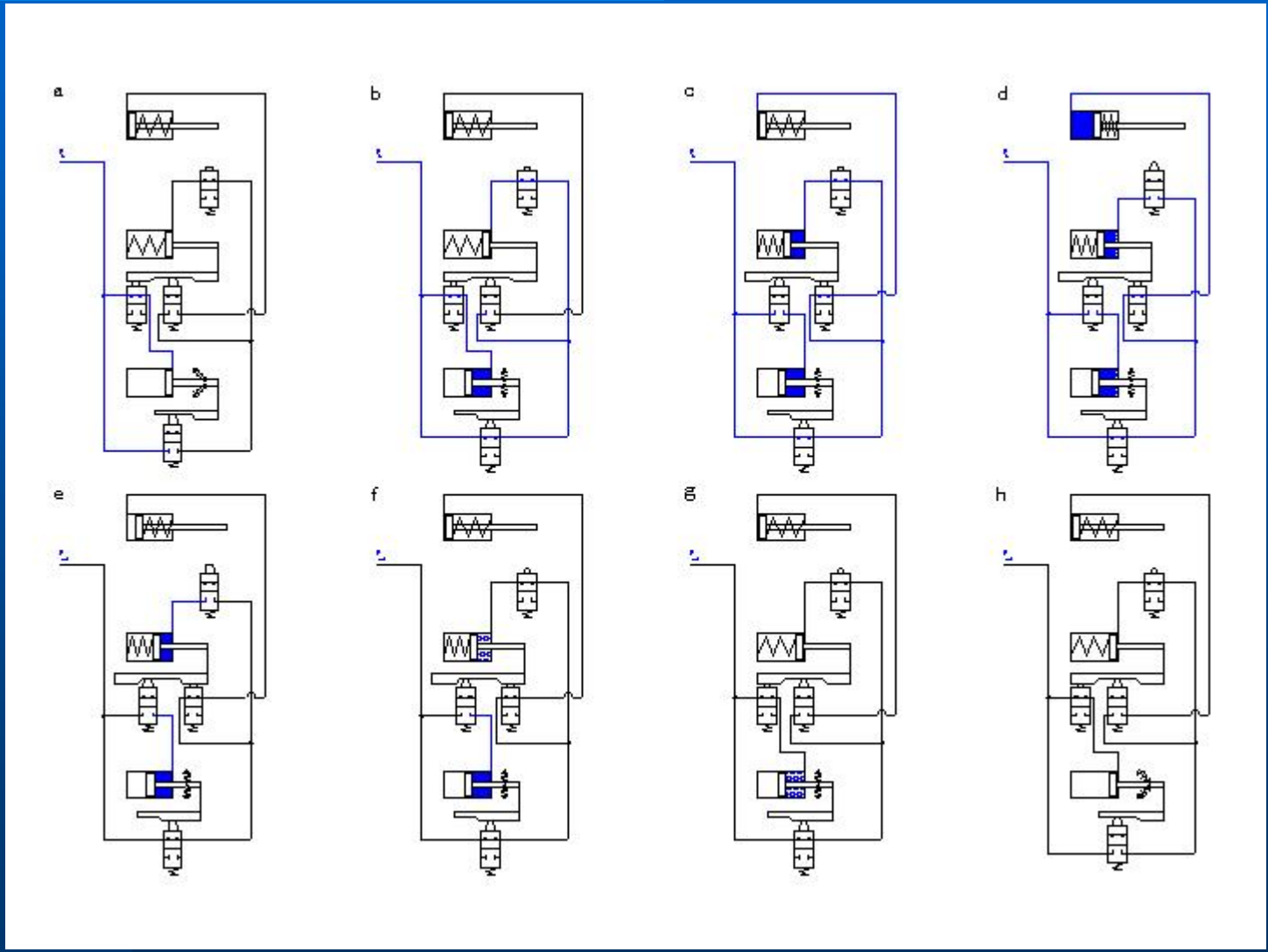


Method – system choice

- **Logical circuit**



Method – system choice



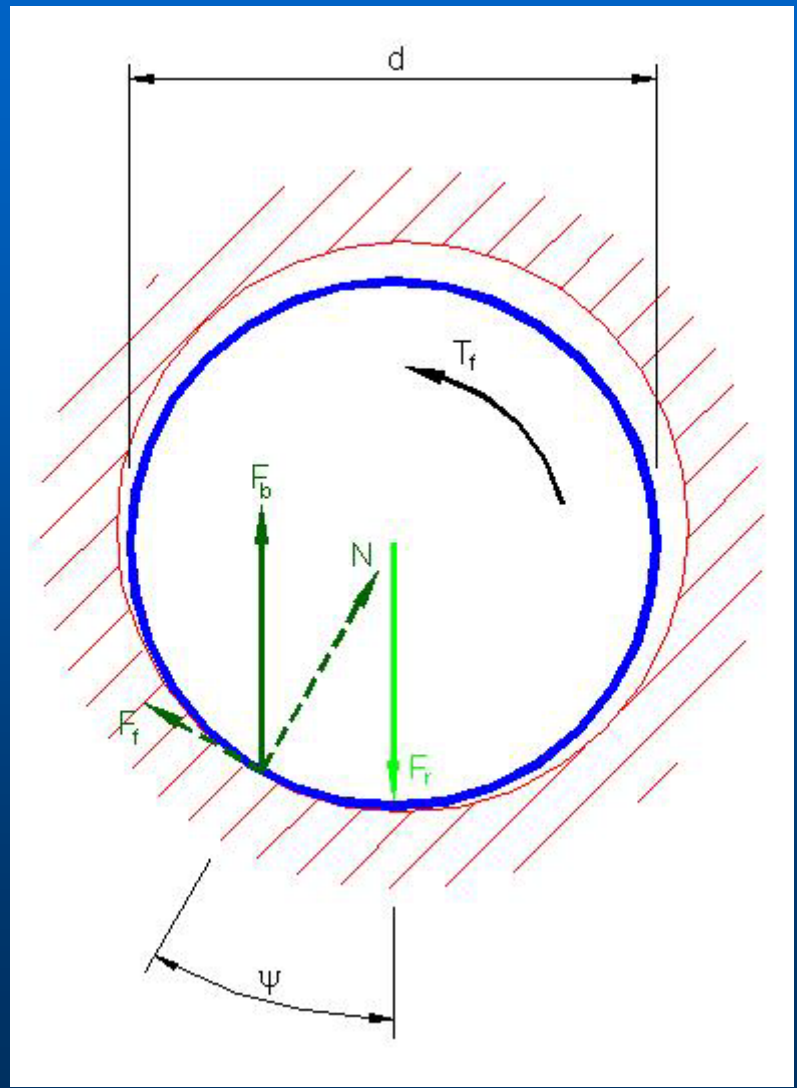
Method – friction losses

- **Pivot point friction:**
  - **Journal bearings**
  - **Ball bearings**
  - **Flexible pivots**
  - **Gas bearings**

Method – friction losses

- **Pivot point friction:**
  - **Journal bearings**

$$T_f = f \cdot F_r \cdot \frac{d}{2}$$



Method – friction losses

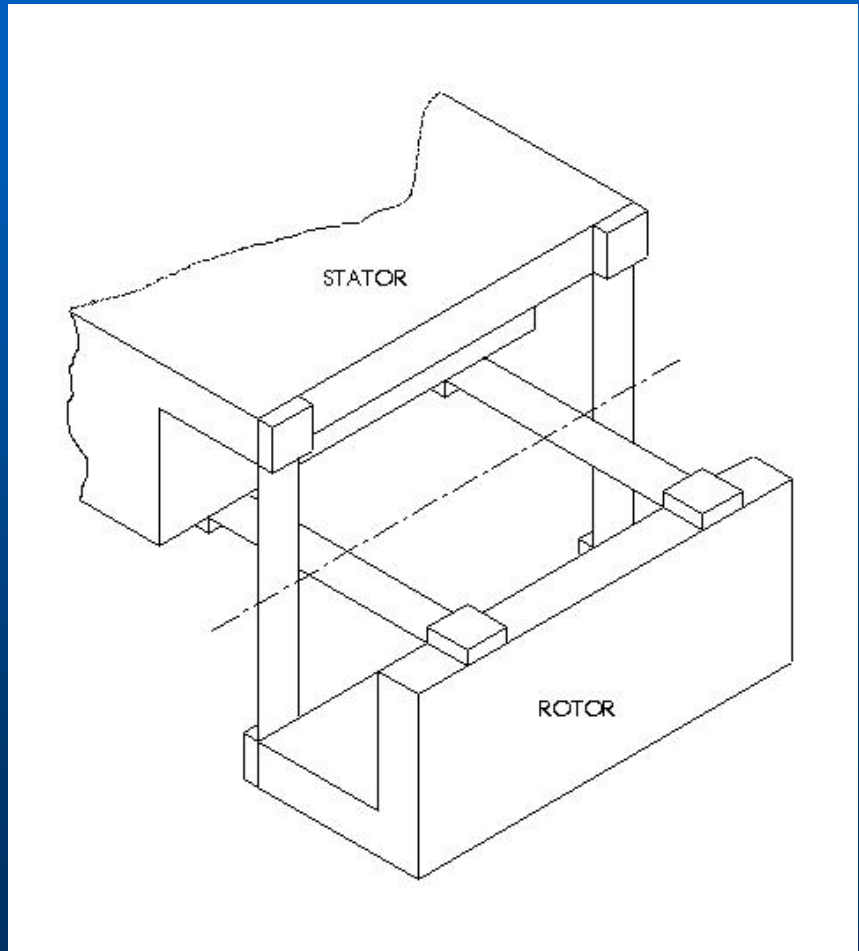
- **Pivot point friction:**
  - **Ball bearings**

$$T_f = 160 \cdot 10^{-7} \cdot f_0 \cdot d_m^3 + f_1 \cdot P_1 \cdot d_m$$

Method – friction losses

- **Pivot point friction:**
  - **Flexible pivot**

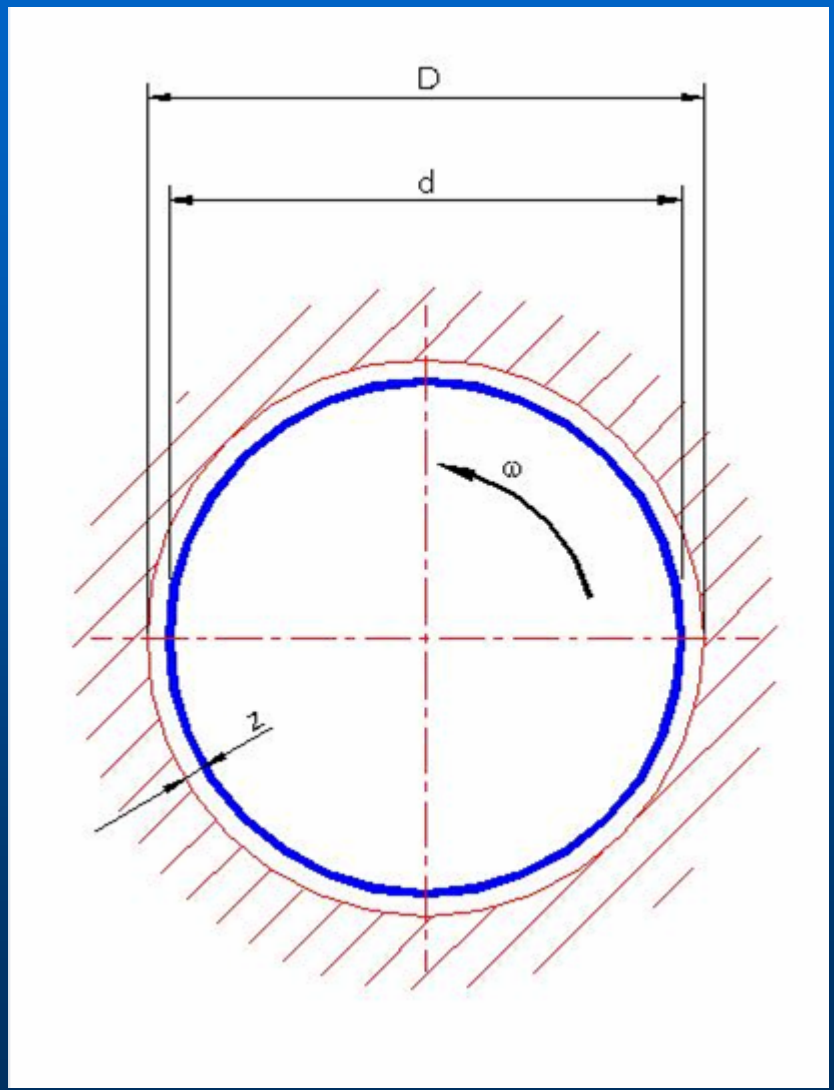
$$T_z = \frac{F_r \cdot d \cdot \varphi}{4 \cdot \pi^2}$$



Method – friction losses

- **Pivot point friction:**
  - **Gas bearings**

$$T_f = \frac{\pi}{4} \cdot \eta \cdot \frac{F_r \cdot d^2}{\alpha \cdot \Delta p} \cdot \frac{\omega}{z}$$



Method – friction losses

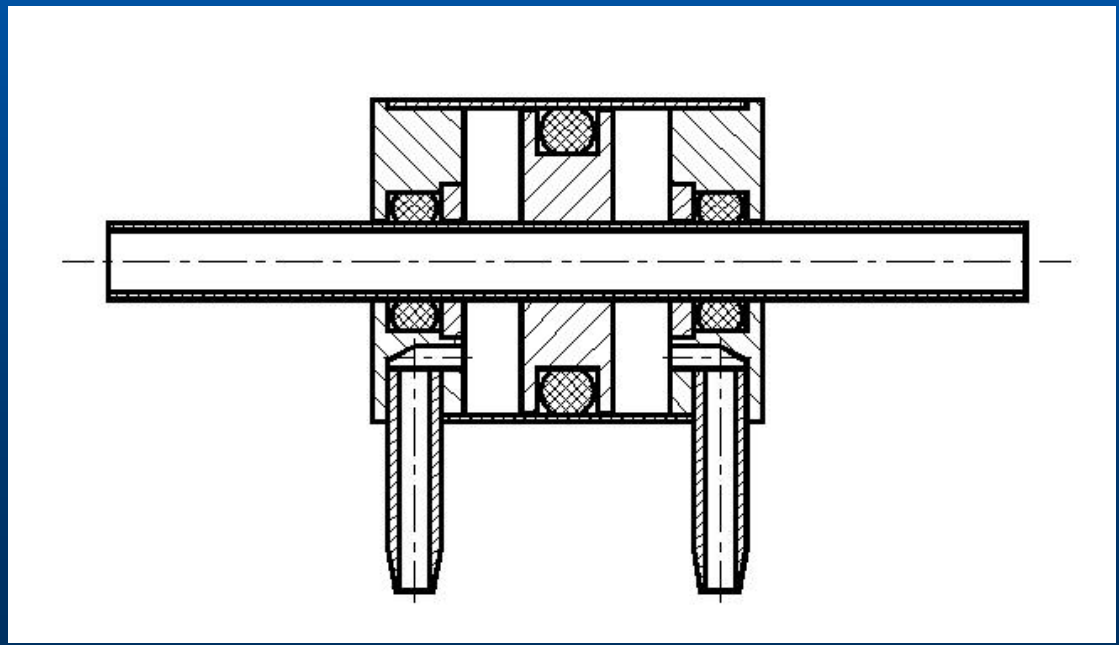
- **Pivot point friction assumptions:**
  - all pivots are loaded with the same force F_r
  - the axis diameter d is the same for all pivot points
  - the rotation angle $\varphi = 30°$, to be travelled in $\Delta t = 0.1$ s

Method – friction losses

- **Pivot point friction:**
  - **Journal bearings** $T_f = 0.05 \cdot F_r \cdot d$
  - **Ball bearings** $T_f \sim 0.0018 \cdot F_r \cdot d$
  - **Flexible pivots** $T_f = 0.013 \cdot F_r \cdot d$
  - **Gas bearings** $T_f = 1 \cdot 10^{-7} \cdot F_r \cdot d^2$

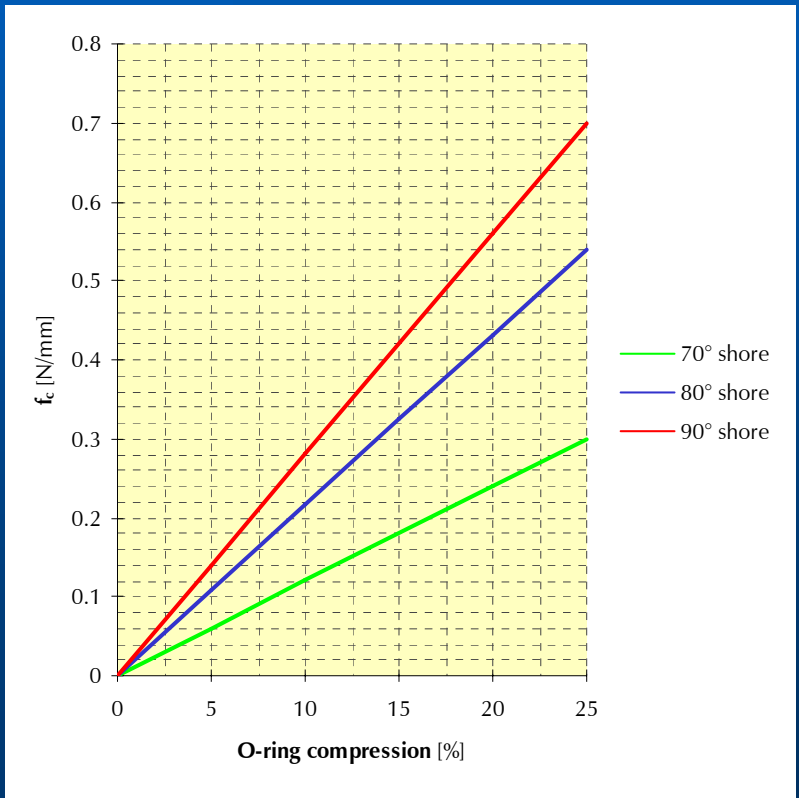
Method – friction losses

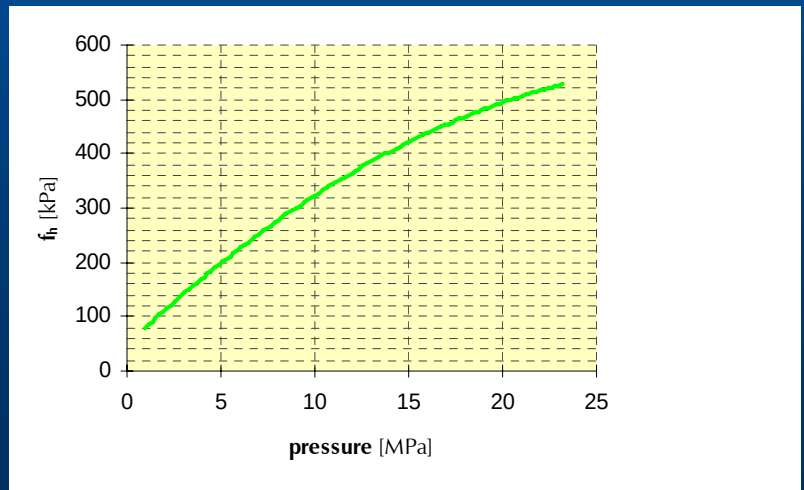
- **Pneumatic seal friction:**
  - **Piston motor**
  - **O-ring seals**



Method – friction losses

- **O-ring seal friction:** $F_f = [f_c \cdot L] + [f_h \cdot A]$

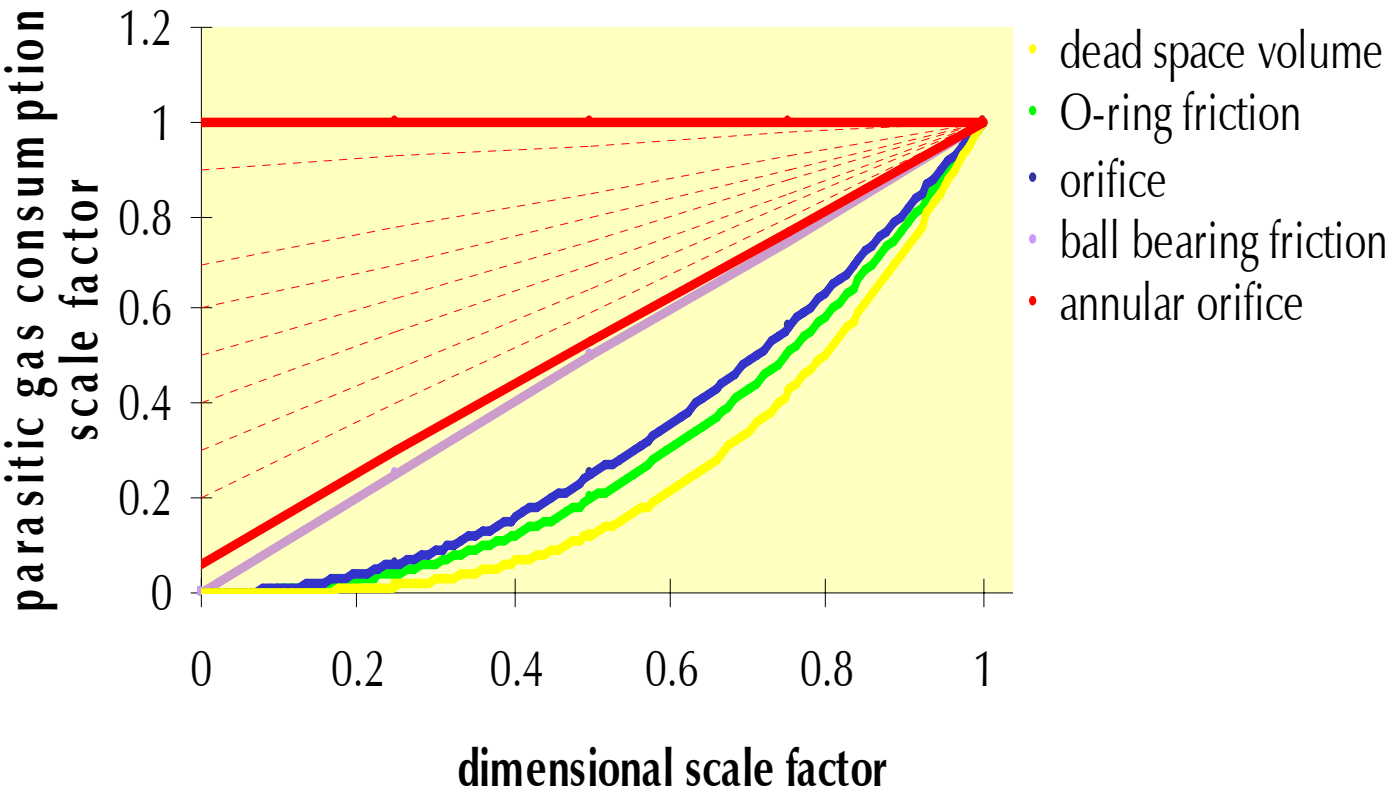




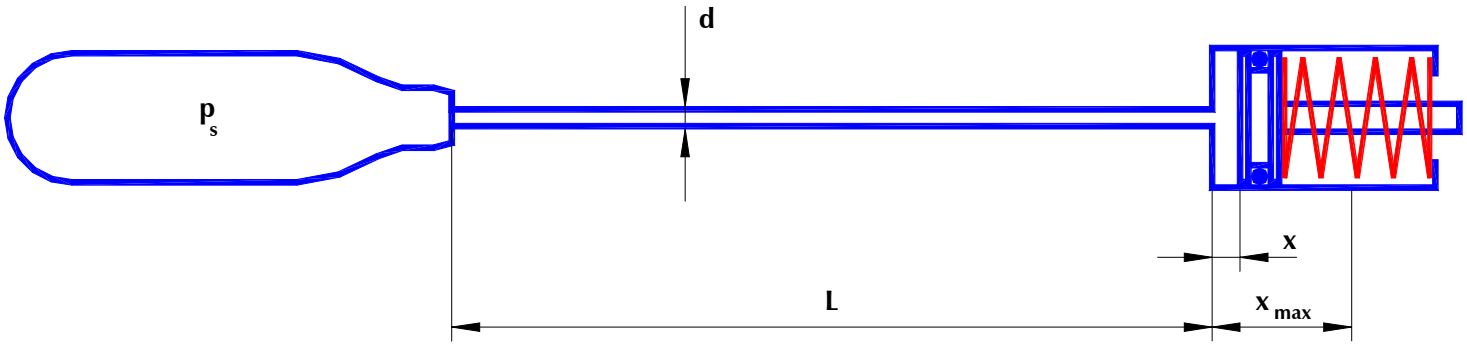
Method – dead space

- $Q_p = \rho \cdot V_{ds}$
- Q_p friction losses?
- Q_p leakage?

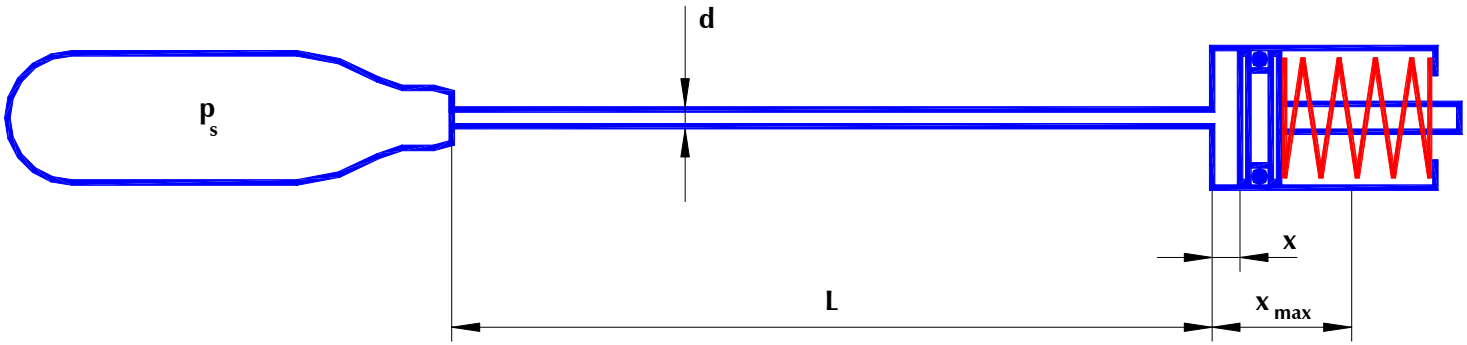
Method – dead space



Method – supply pressure



Method – supply pressure



$$m_{hc} = \rho \cdot \left[V_p + V_c \right] = \rho \cdot \left[\frac{\pi}{4} \cdot d^2 \cdot L + x \cdot A_c \right]$$

Method – supply pressure

$$m_{hc} = \rho \cdot \left[V_p + V_c \right] = \rho \cdot \left[\frac{\pi}{4} \cdot d^2 \cdot L + x \cdot A_c \right]$$

Optimal supply pressure level from:

$$\frac{dm_{hc}}{dp_s} = \frac{d}{dp_s} \left[\rho \cdot \left[\frac{\pi}{4} \cdot d^2 \cdot L + x \cdot A_c \right] \right] = 0$$

Method – supply pressure

$$\frac{dm(p_s)}{dp_s} = \frac{\frac{32\cdot\eta\cdot L^2}{t}\cdot(0.01\cdot T)^{3.333}\cdot\left[\left[R\cdot T\cdot(0.01\cdot T)^{3.333}+12.4915\cdot(p_s+p_a)^2\right]\cdot\left[\left[\frac{F_{top}\cdot(2\cdot F_{top}-F_0)}{c\cdot p_s^2}+\frac{107.483}{(0.01\cdot T)^{3.333}}\right]\cdot\ln\left[\frac{F_0-F_{top}}{c\cdot x+F_0-F_{top}}\right]+\left[\frac{F_{top}\cdot(2\cdot F_{top}+F_0)}{c\cdot p_s^2}-\frac{57.517}{(0.01\cdot T)^{3.333}}\right]\cdot\ln\left[\frac{F_0+F_{top}}{c\cdot x+F_0+F_{top}}\right]\right]-\right.}{\left.-(p_s+p_a)\cdot\left[\frac{F_{top}\cdot(2\cdot F_{top}-F_0)}{c\cdot p_s^3}\cdot\ln\left[\frac{F_0-F_{top}}{c\cdot x+F_0-F_{top}}\right]+\frac{F_{top}\cdot(2\cdot F_{top}+F_0)}{c\cdot p_s^3}\cdot\ln\left[\frac{F_0+F_{top}}{c\cdot x+F_0+F_{top}}\right]\right]\cdot\left[R\cdot T\cdot(0.01\cdot T)^{3.333}-82.5\cdot(p_s+p_a)-12.4915\cdot(p_s+p_a)^2\right]\right]}+$$

$$\left[R\cdot T\cdot(0.01\cdot T)^{3.333}-82.5\cdot(p_s+p_a)-12.4915\cdot(p_s+p_a)^2\right]^2\cdot\sqrt{\frac{128\cdot\eta\cdot L}{\pi\cdot t}\left[\left[\frac{F_{top}\cdot(2\cdot F_{top}-F_0)}{c\cdot p_s^2}+\frac{107.483}{(0.01\cdot T)^{3.333}}\right]\cdot\ln\left[\frac{F_0-F_{top}}{c\cdot x+F_0-F_{top}}\right]+\right.}$$

$$\left.+\left[\frac{F_{top}\cdot(2\cdot F_{top}+F_0)}{c\cdot p_s^2}-\frac{57.517}{(0.01\cdot T)^{3.333}}\right]\cdot\ln\left[\frac{F_0+F_{top}}{c\cdot x+F_0+F_{top}}\right]\right]}+$$

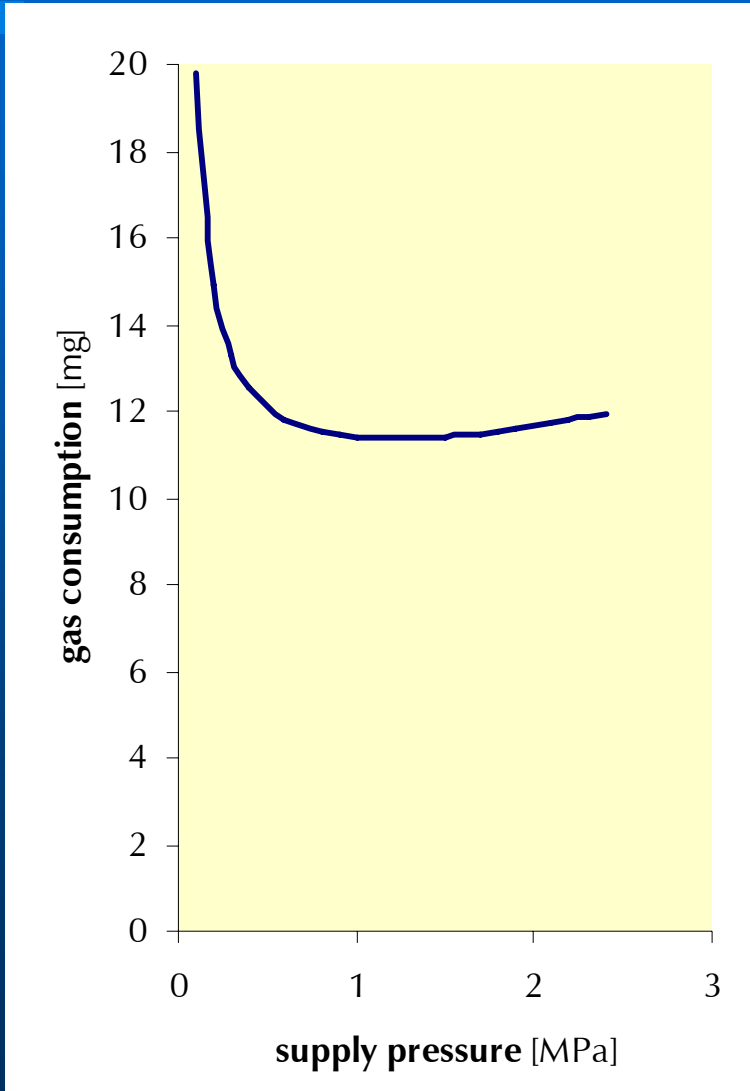
$$+\frac{x\cdot F_{top}}{p_s^2}\cdot\left[\frac{12.4915\cdot(p_s+p_a)^3\cdot(0.01\cdot T)^{3.333}+(p_s+p_a)^2\cdot(0.01\cdot T)^{3.333}\cdot(82.5+12.4915\cdot p_s)-p_a\cdot R\cdot T\cdot\left[(0.01\cdot T)^{3.333}\right]^2}{\left[R\cdot T\cdot(0.01\cdot T)^{3.333}-82.5\cdot(p_s+p_a)-12.4915\cdot(p_s+p_a)^2\right]^2}\right]=0$$

Method – supply pressure

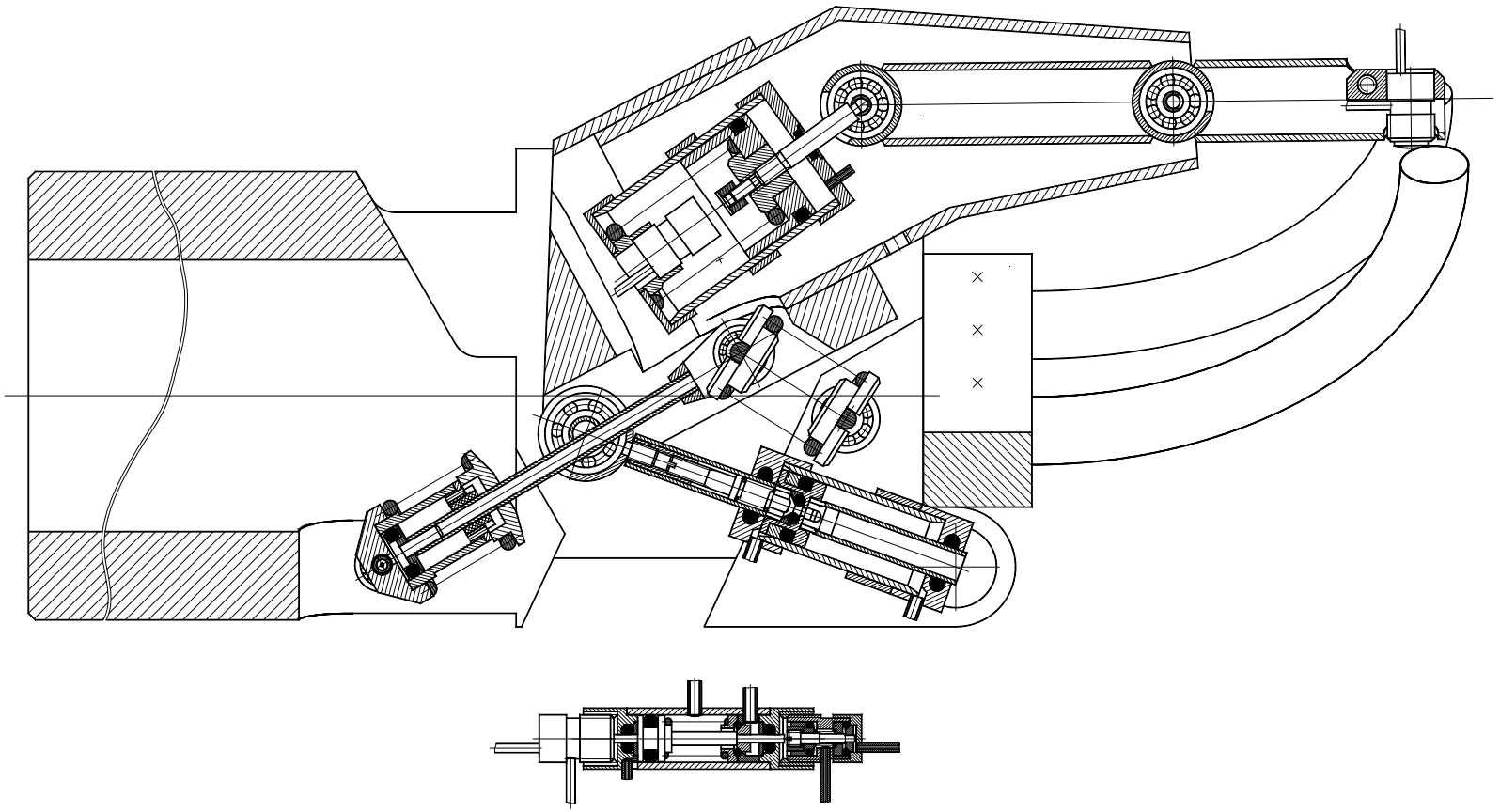
$P_{s,\,opt} = 1.2$ MPa

Independent of:

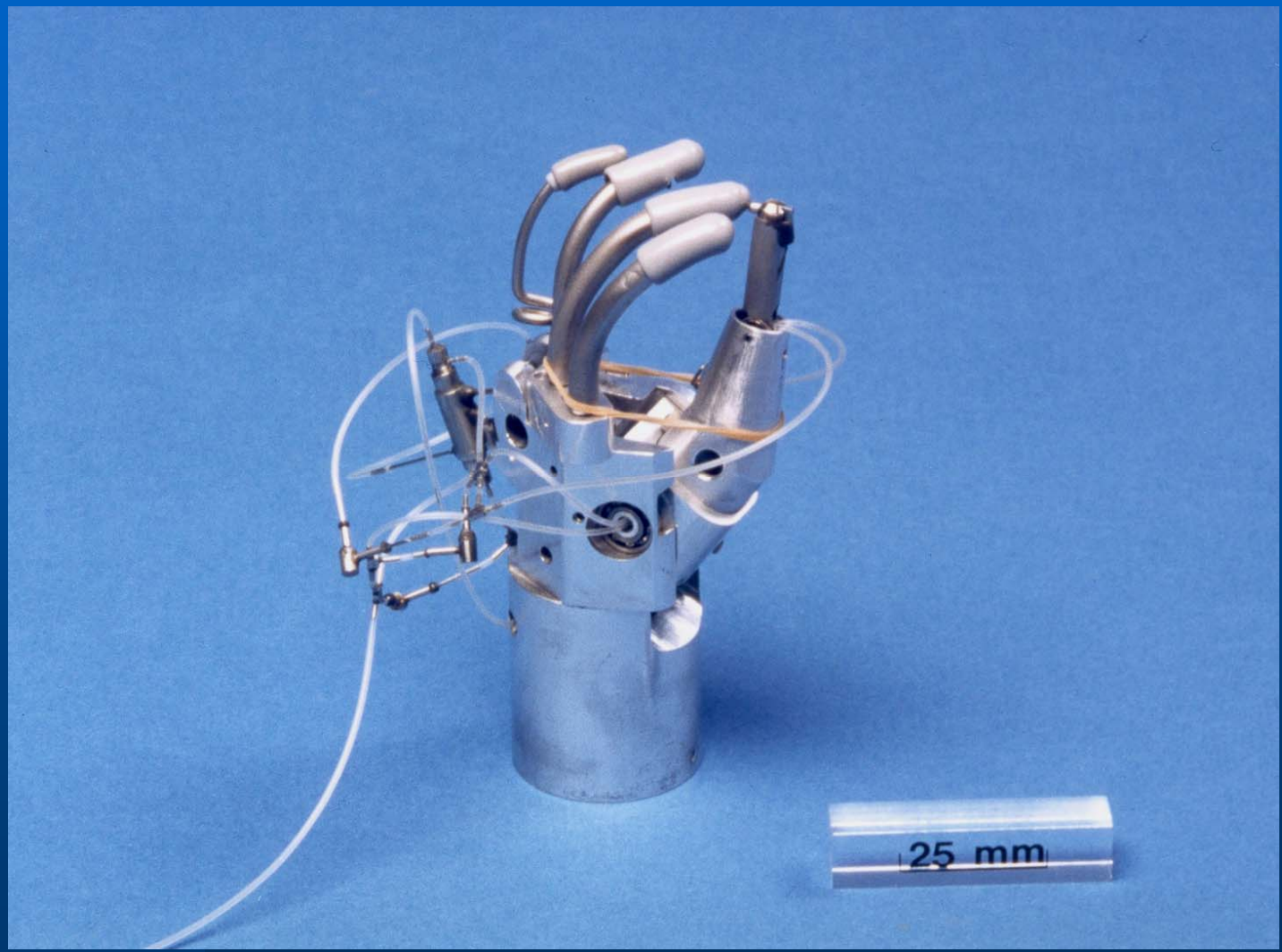
Δt, L, F_s, and x



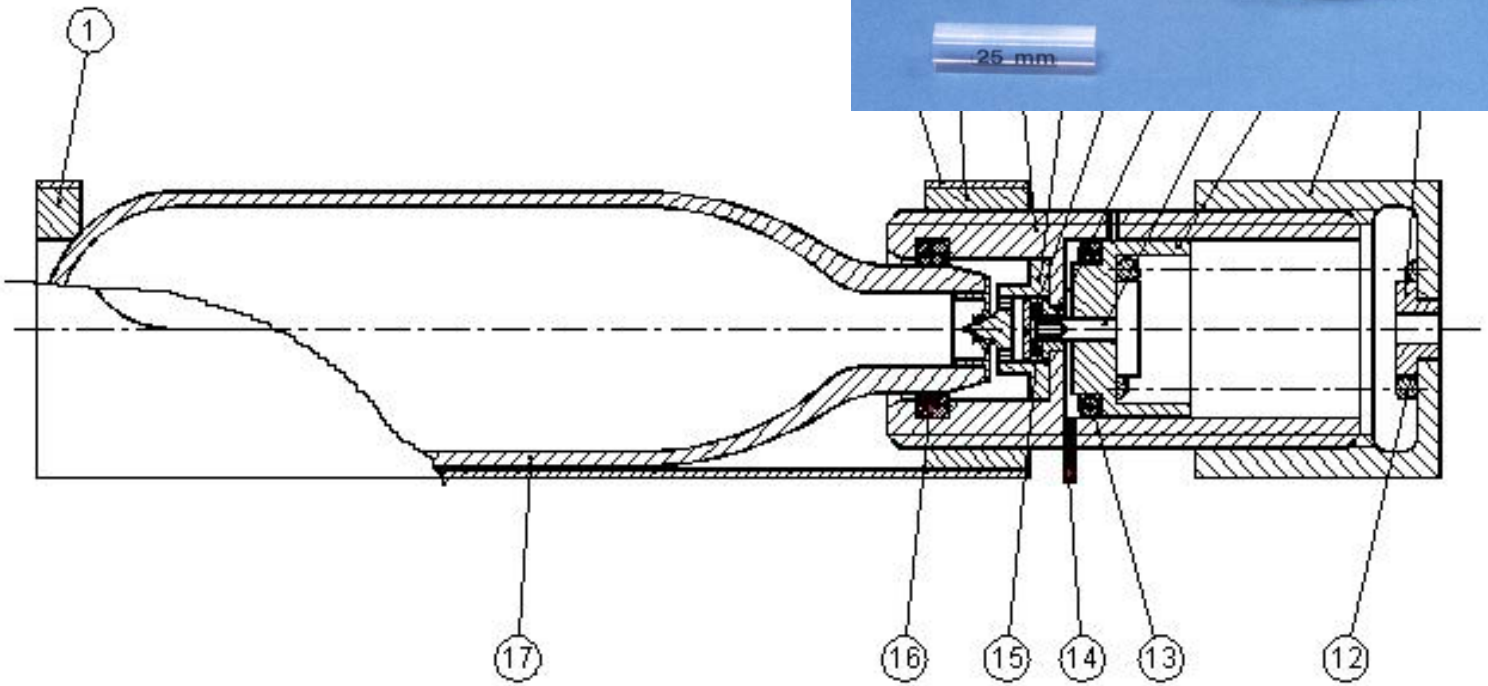
Method – prototype I



Results I



Results I

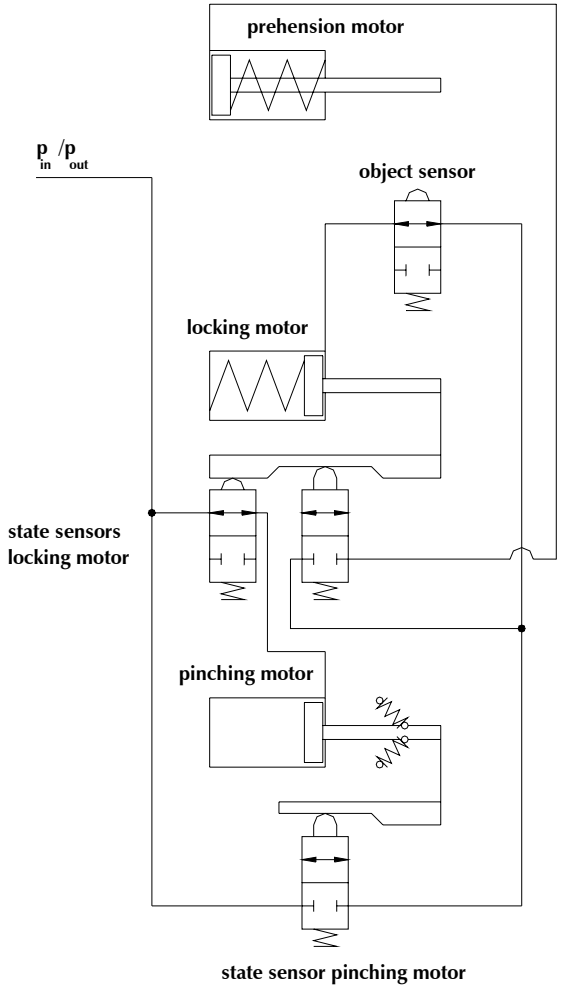


Results I

- Addition of check valves
- Pneumatic switch
- Glove compensation

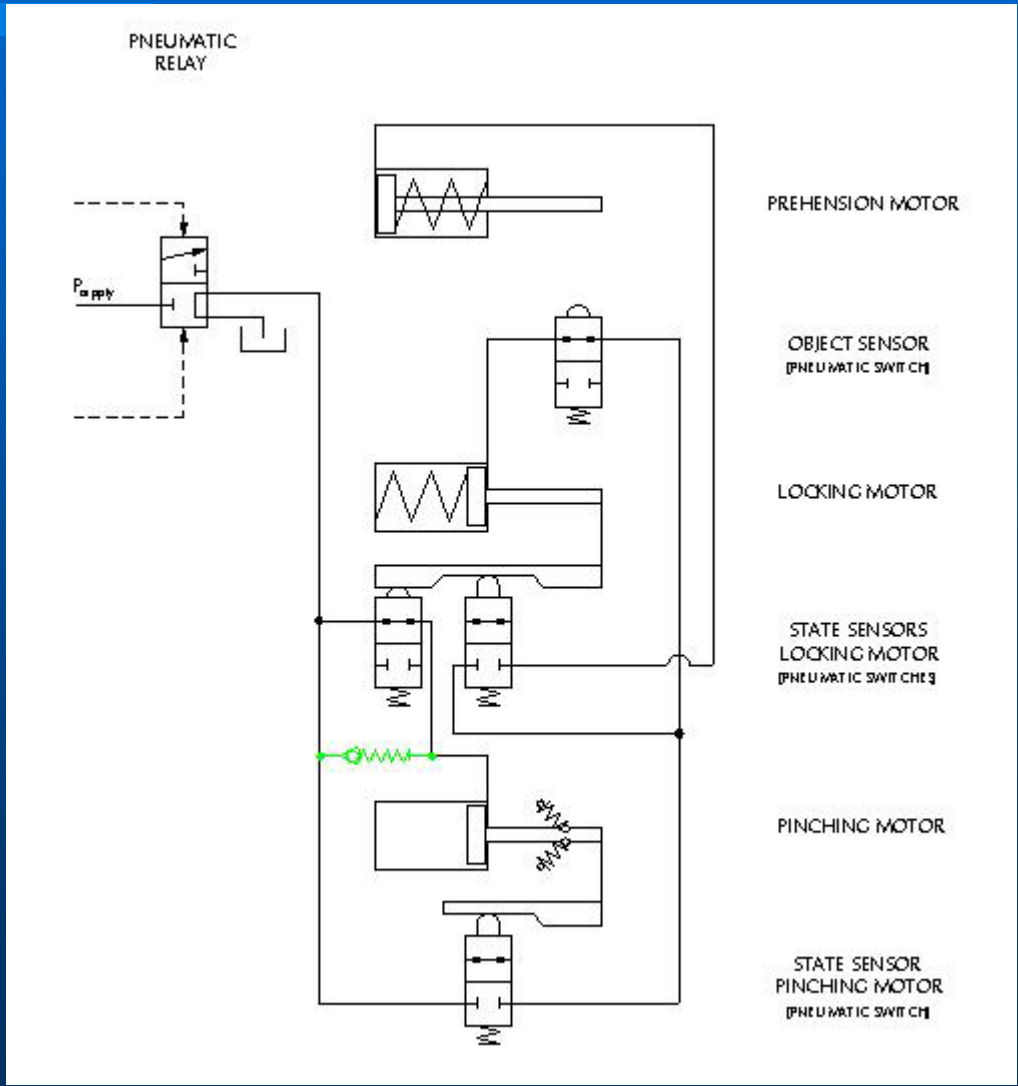
Results I

- **Logical circuit**



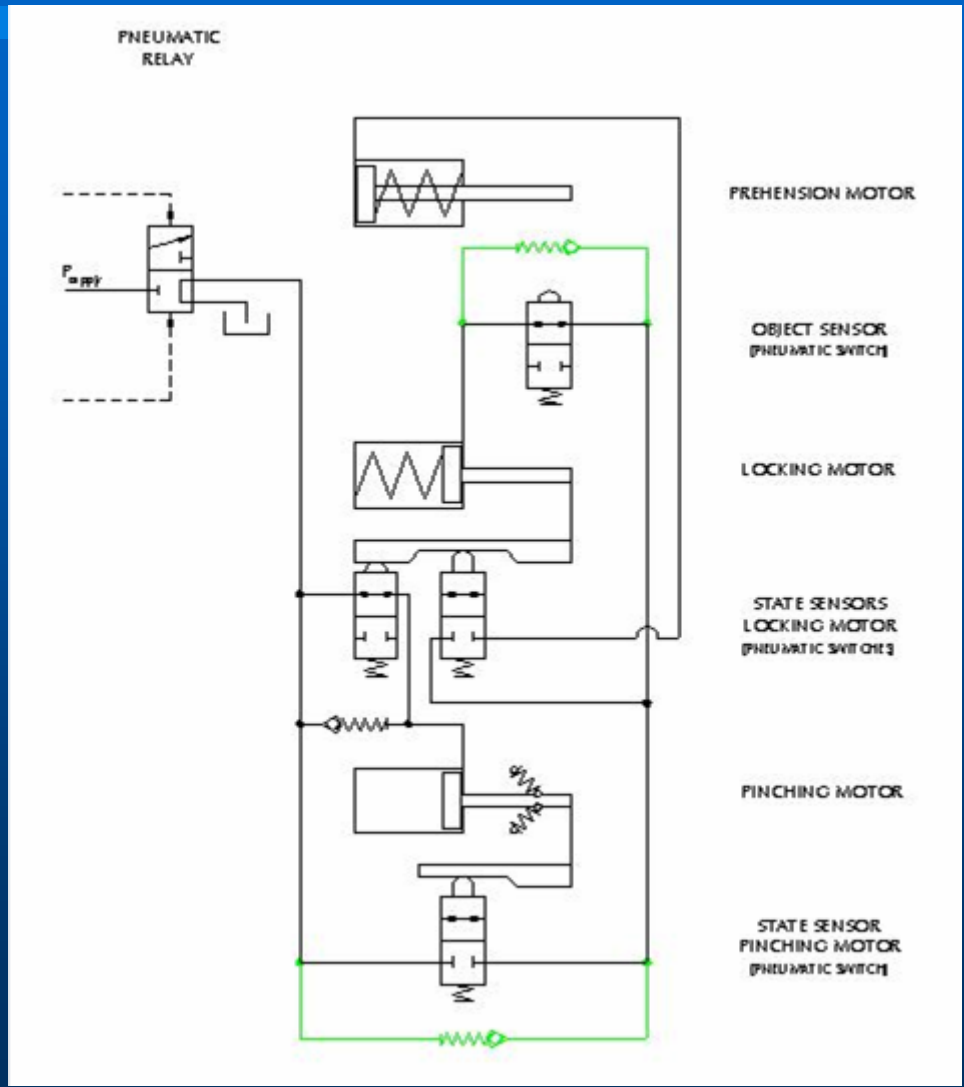
Results I

- **Logical circuit**



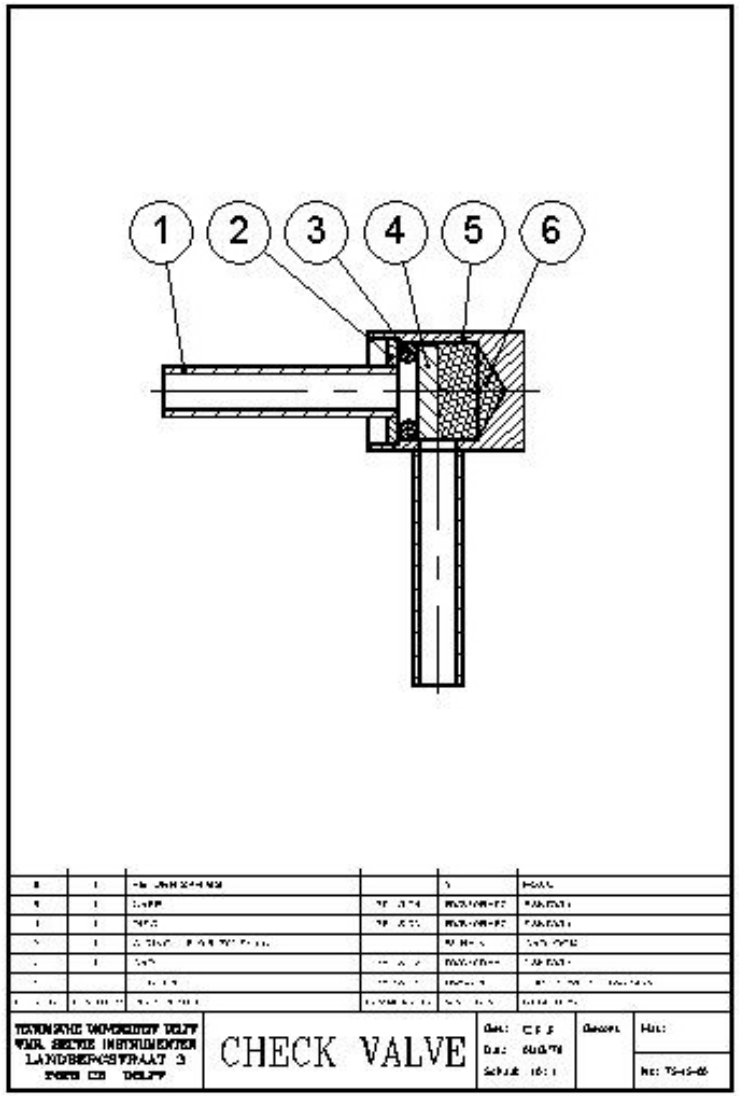
Results I

- **Logical circuit**



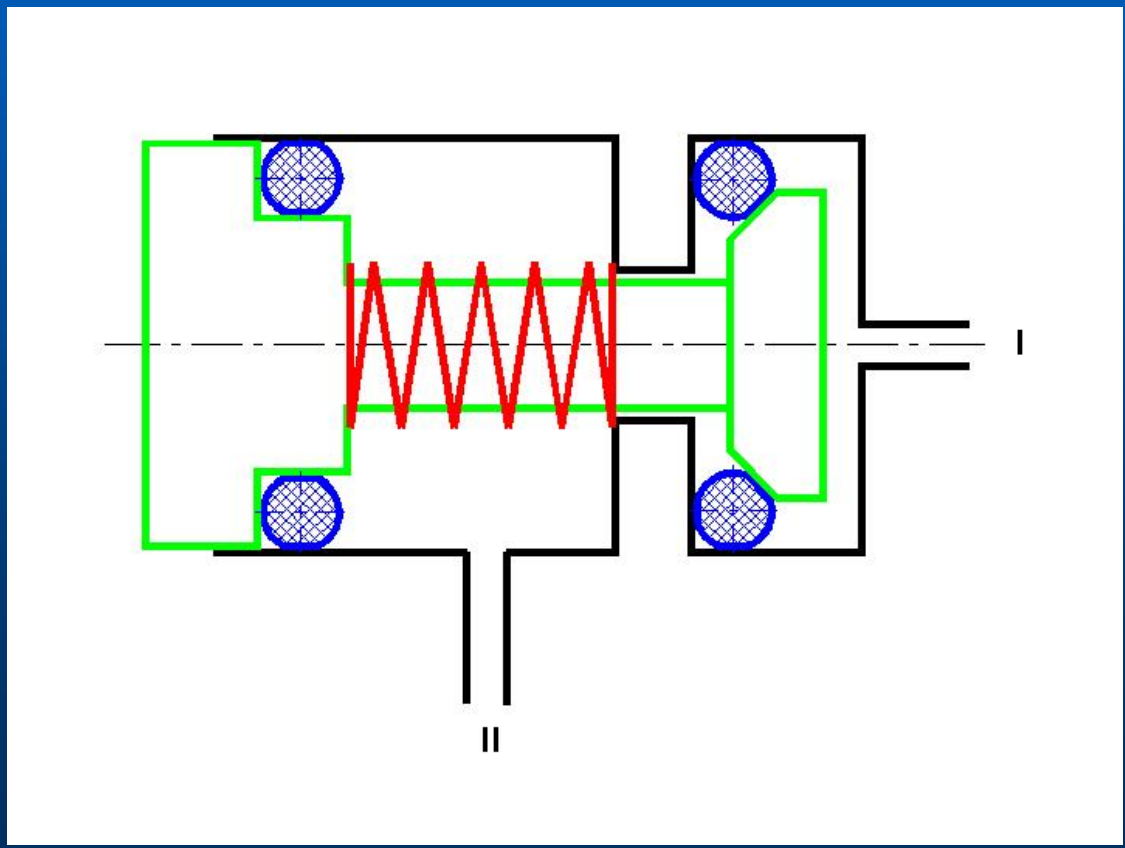
Results I

- **'Old timer' check valve**

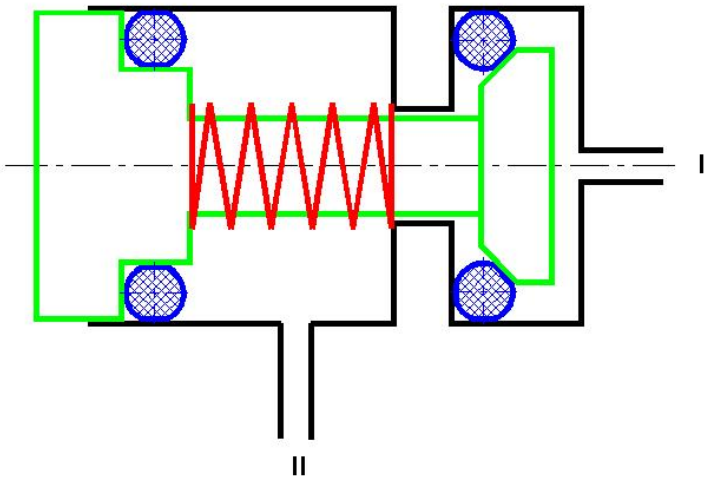


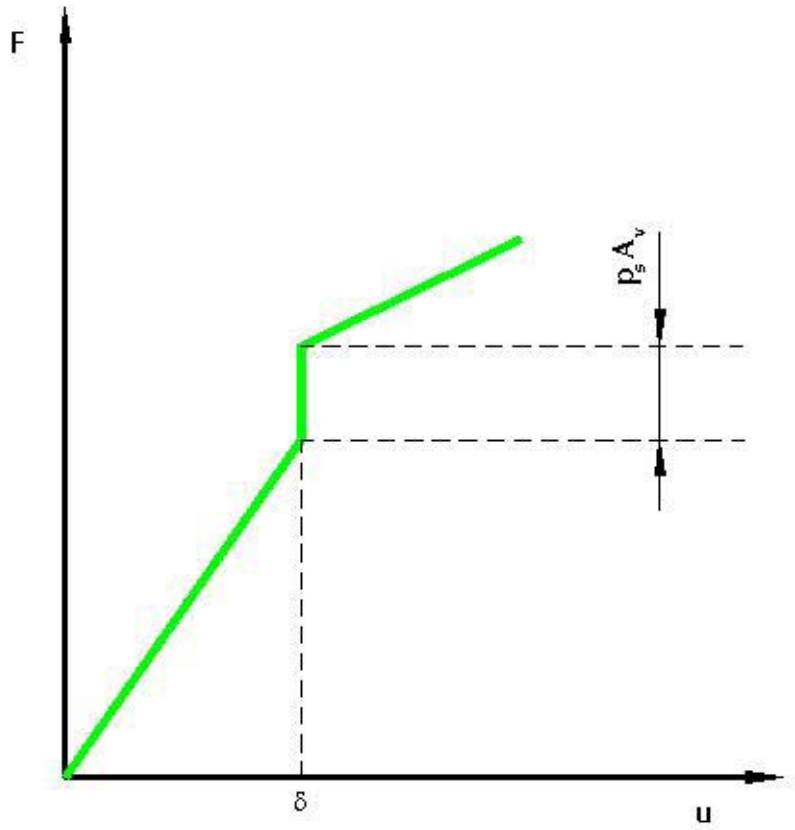
Results I

- **Pneumatic switch**

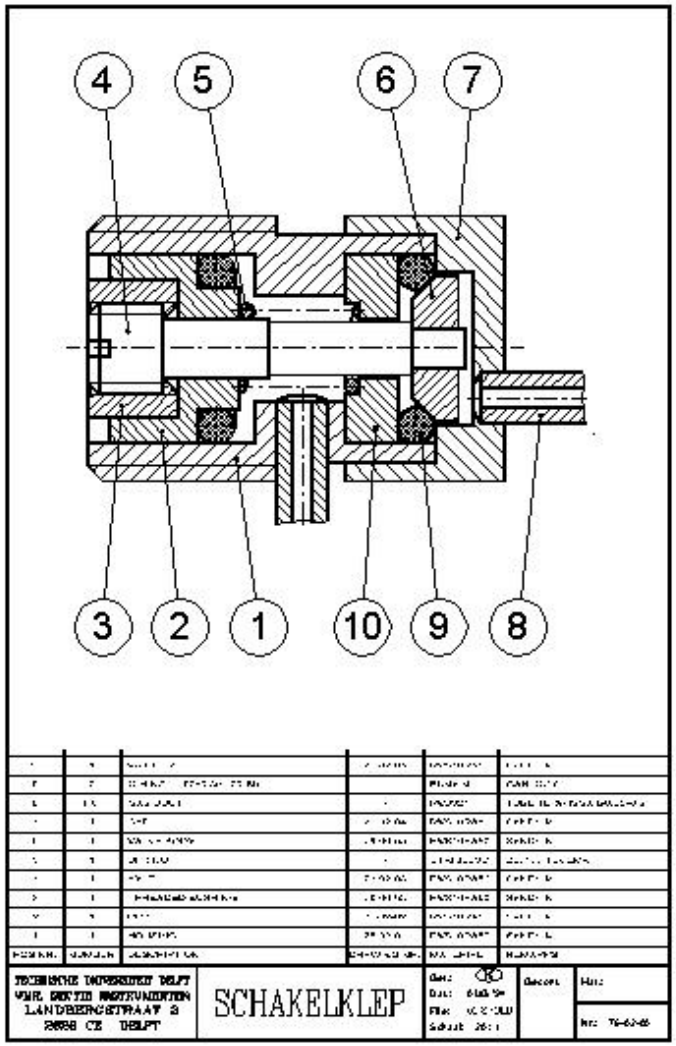


Results I



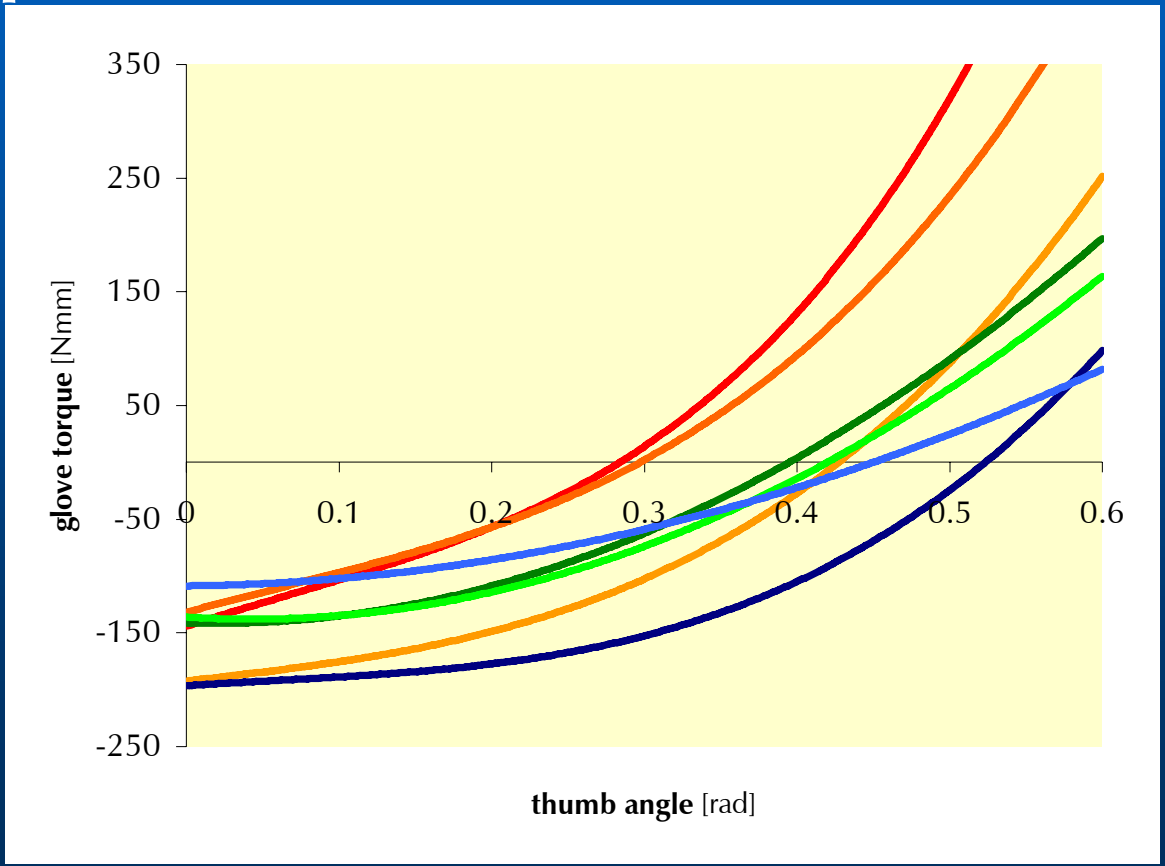


Results I



Results I

- **Glove compensation**



Results I

- **Endurance test: 77000 cycles**

Results I

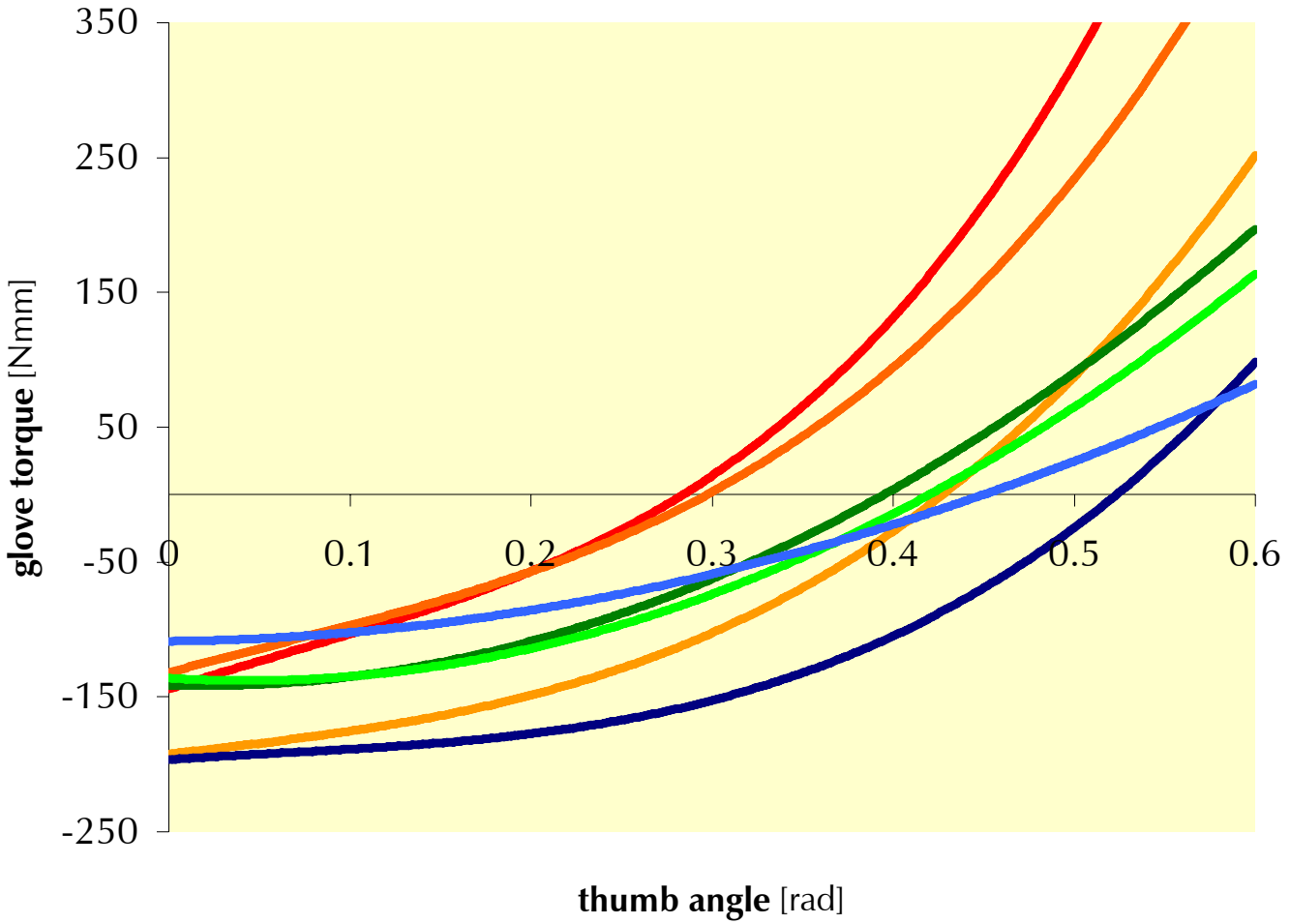
	MYOELECTRIC STEEPER	MYOELECTRIC OTTO BOCK	PNEUMATIC WILMER
MASS OF THE HAND [grams]	230	130	128
MASS OF THE ENERGY STORAGE SYSTEM [grams]	75	60	60
MASS OF THE COMPLETE PROSTHESIS [grams]	550	340	300*
ELBOW TORQUE [Nmm]	760	470	400*
ENERGY CONSUMPTION [per day]	1 BATTERY	1 BATTERY	0.5 GAS CONTAINER
OPERATING CYCLE [seconds]	2.5	>2.5	<1

* estimated figure

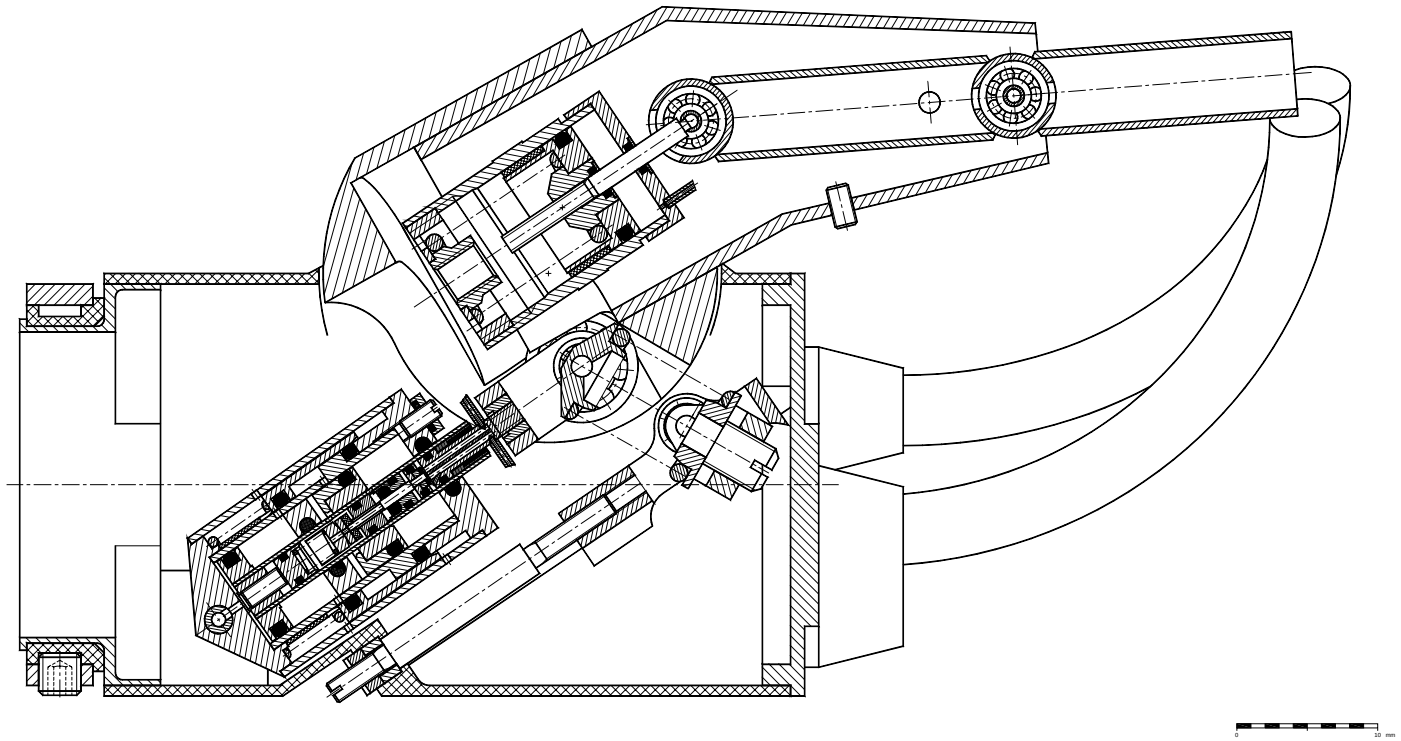
Method – prototype II

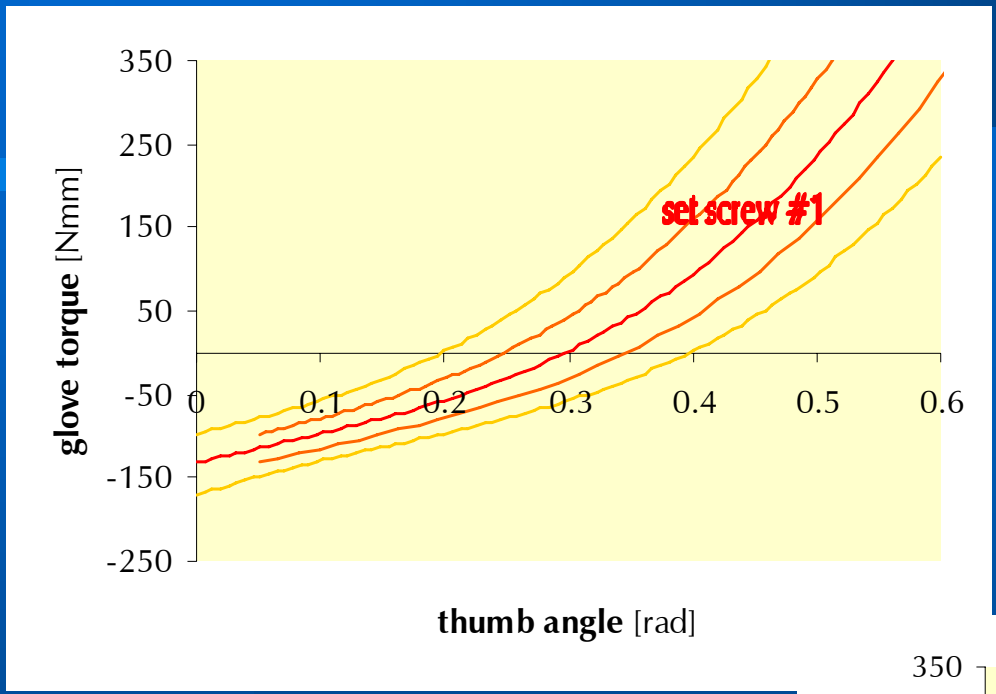
- Glove compensation
- Mass of frame
- Pneumatical switch
- Check valve

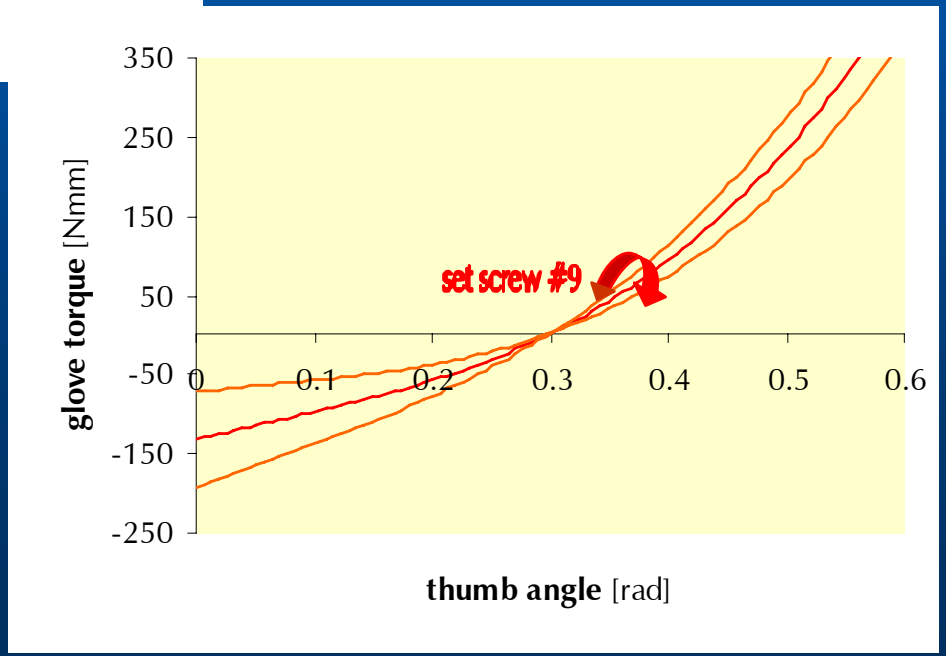
Method – prototype II



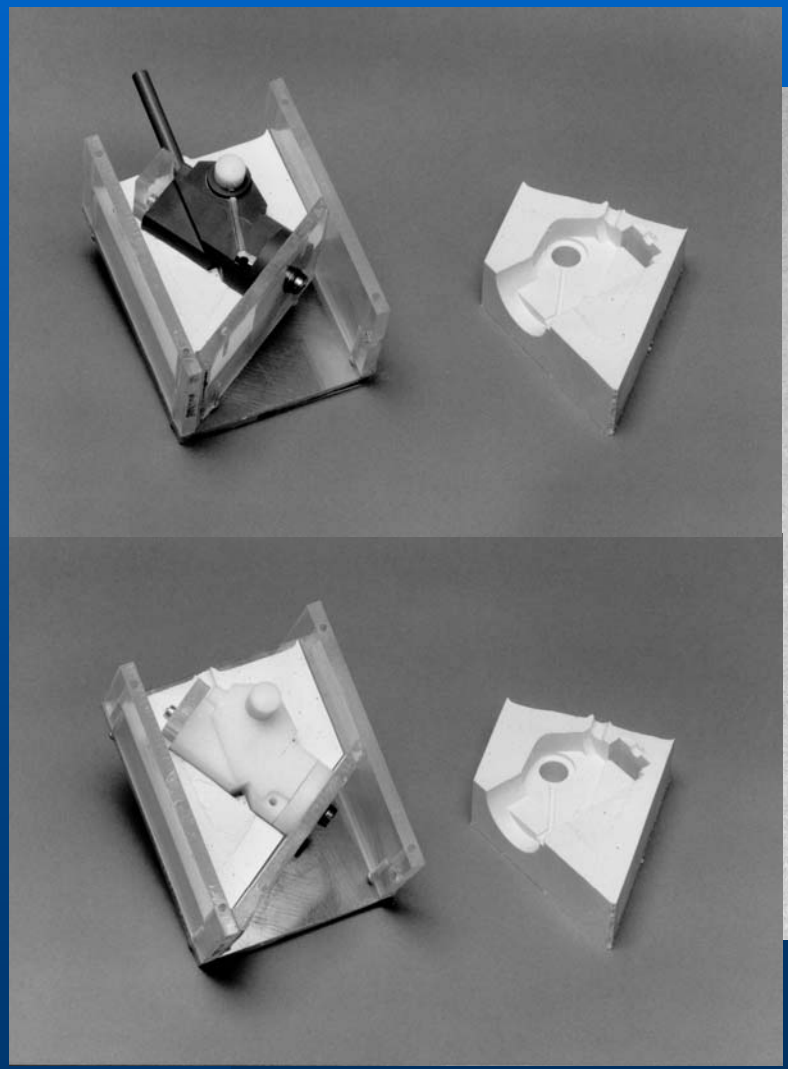
Method – prototype II



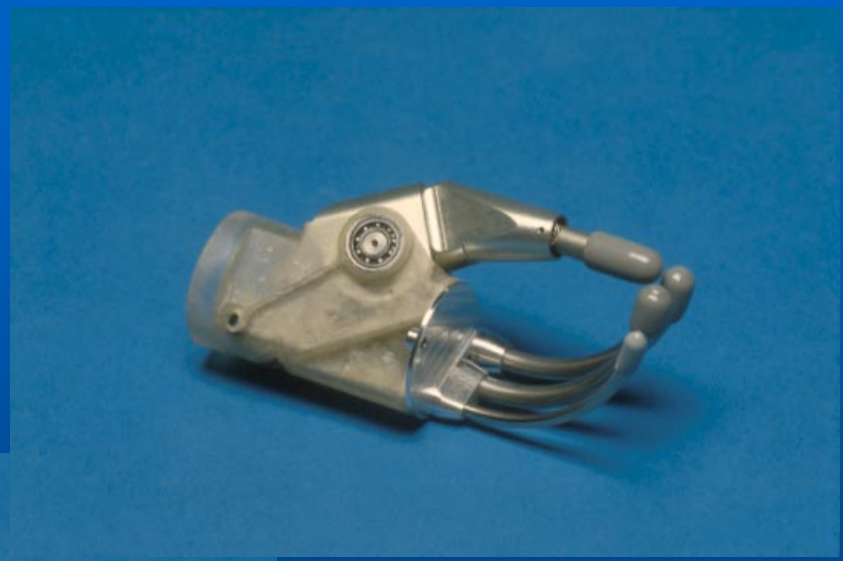

350
250
150
50
-50
-150
-250
0
0.1
0.2
0.3
0.4
0.5
0.6
glove torque [Nmm]
thumb angle [rad]
set screw #1


350
250
150
50
-50
-150
-250
0
0.1
0.2
0.3
0.4
0.5
0.6
glove torque [Nmm]
thumb angle [rad]
set screw #9

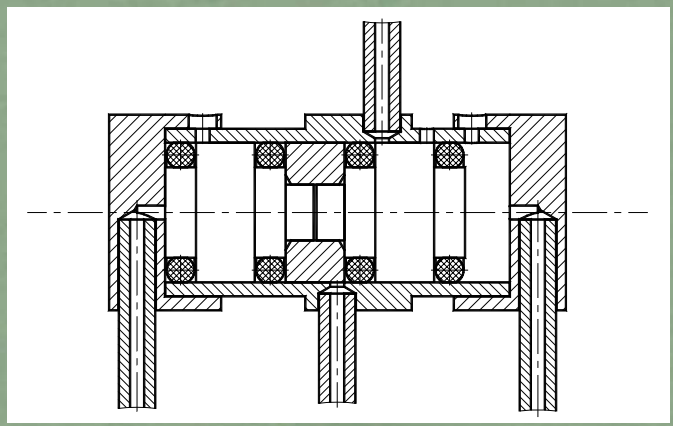
Method – prototype II

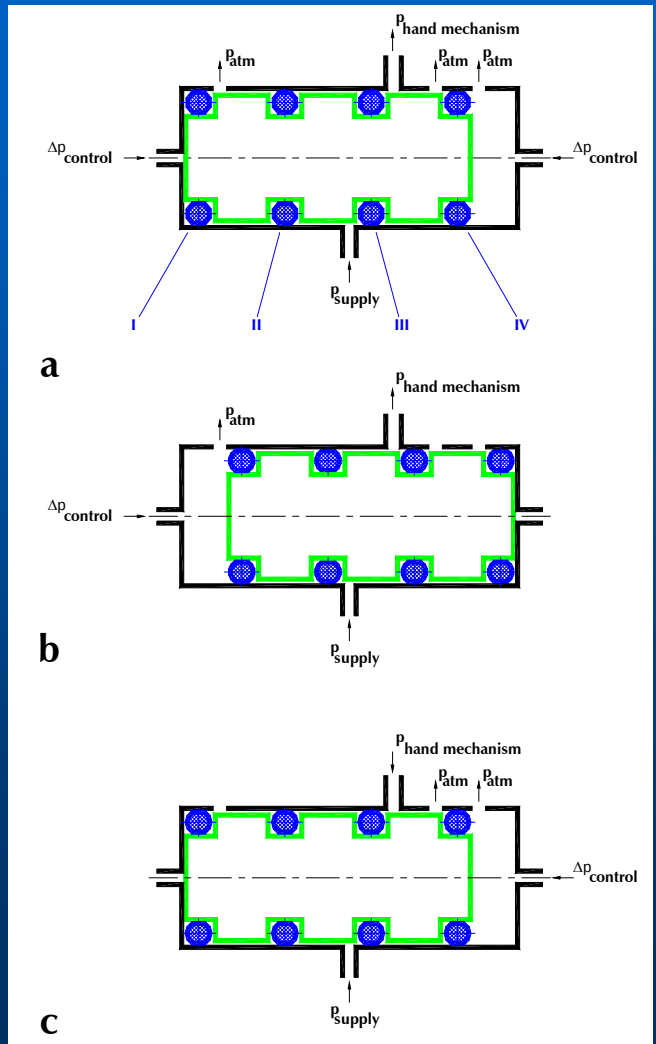


Method – prototype II

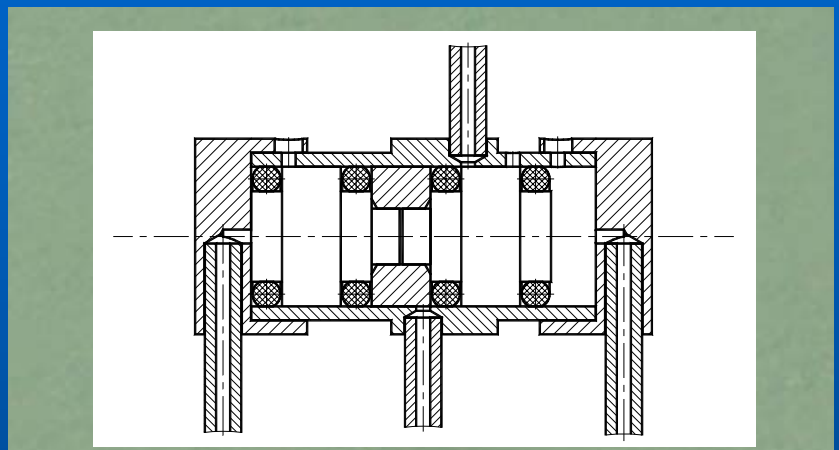


Method – prototype II





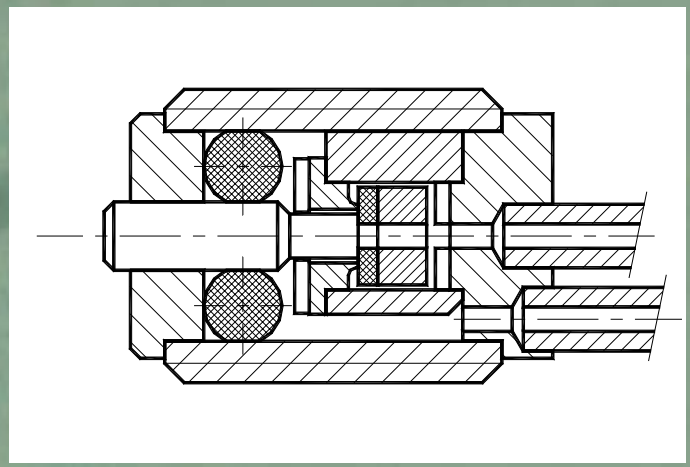
Method – prototype II



Pneumatic relay:

- Ø 3.5 x 8.15 mm
- $\Delta P = 0.4$ MPa
- $Q = 74.2$ ltr/hr
- $m = 0.66$ g

Method – prototype II

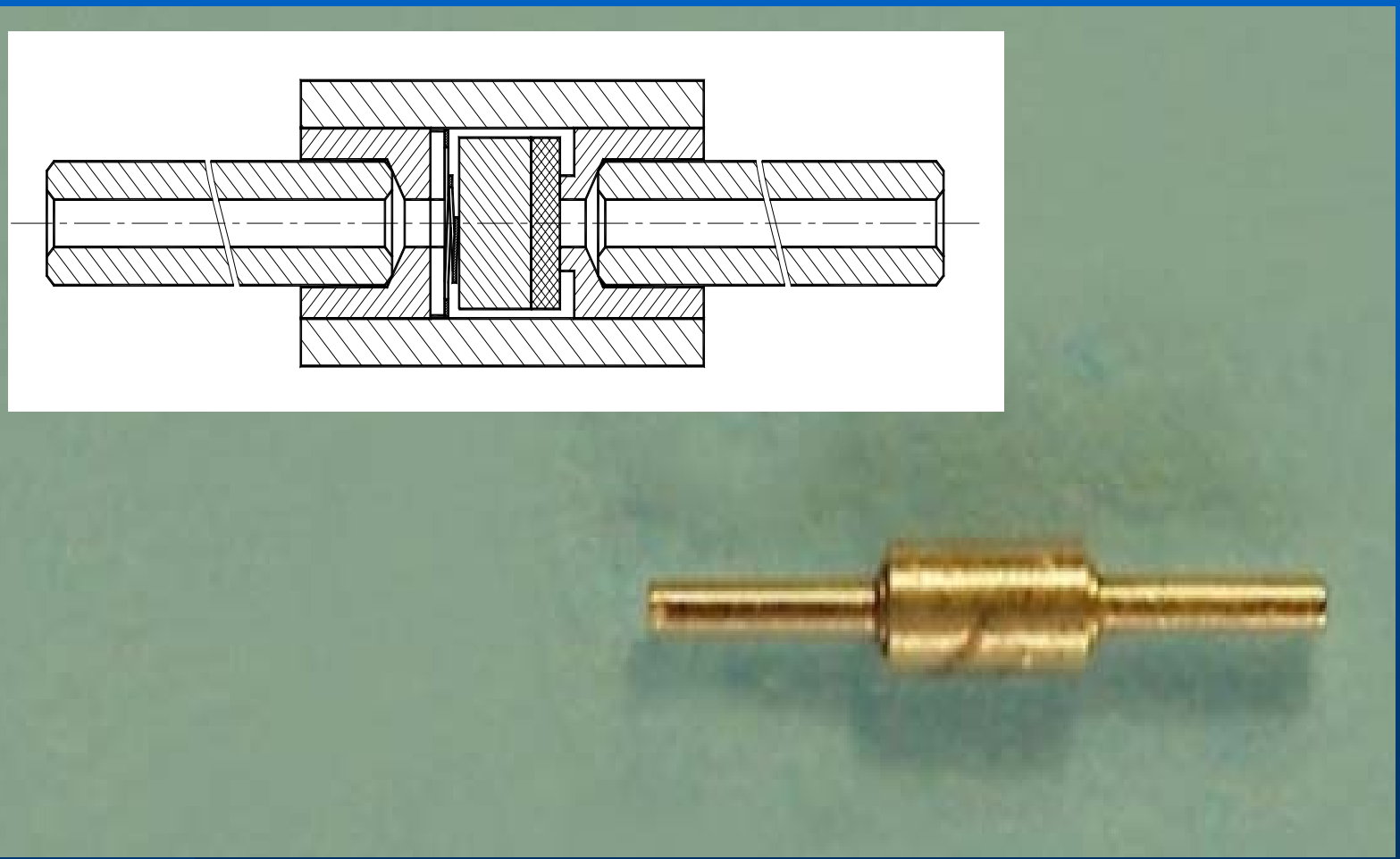


Method – prototype II

Pneumatic switch:

- **Ø 3.0 x 4.3 mm**
- **F = 0.6 N**
- **Q = 97.0 ltr/hr**
- **m = 0.19 g**

Method – prototype II



Method – prototype II

Check valve:

- Ø 1.5 x 2.8 mm

- $\Delta P = 48$ kPa

- $Q \geq 120.0$ ltr/hr

- $m = 0.05$ g

Results II

	MYOELECTRIC STEEPER	MYOELECTRIC OTTO BOCK	PNEUMATIC TECHNICAL PROTOTYPE WILMER	PNEUMATIC CLINICAL PROTOTYPE WILMER
MASS OF THE HAND [grams]	230	130	128	60
MASS OF THE ENERGY STORAGE SYSTEM [grams]	75	60	60	36**
MASS OF THE COMPLETE PROSTHESIS [grams]	550	340	300*	250*
ELBOW TORQUE [Nmm]	760	470	400*	290*
ENERGY CONSUMPTION [per day]	1 BATTERY	1 BATTERY	0.5 GAS CONTAINER	< 0.5 GAS CONTAINER
OPERATING CYCLE [seconds]	2.5	>2.5	<1	<1

* estimated figure
** estimated figure, based upon a mass for the pressure reducing valve of 4 grams after a redesign

Concluding remarks

- **Pneumatic actuation excels electrical actuation:**
  - **Low in mass**
  - **Fast**
  - **Reliable**
  - **Small**

Concluding remarks

- **Clinical evaluation**
- **Pneumatic servo mechanism**
- **Miniature pneumatic components**

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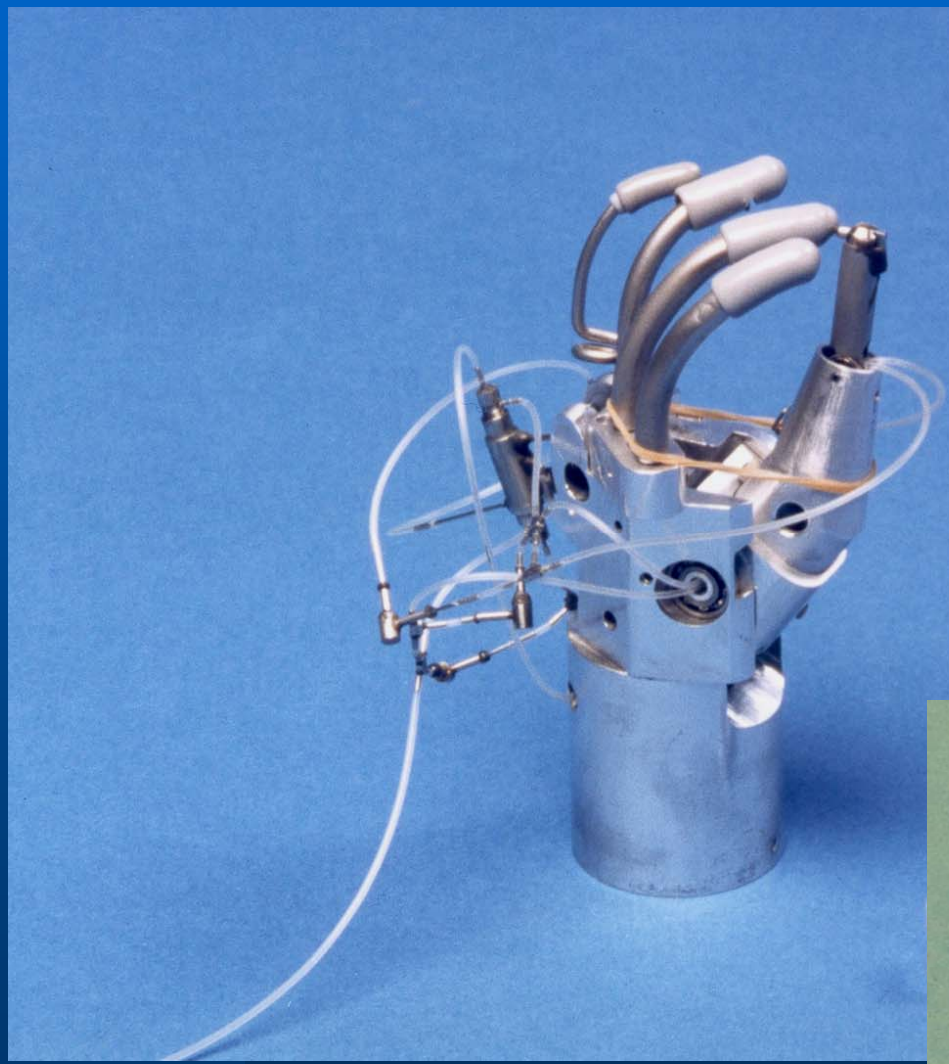

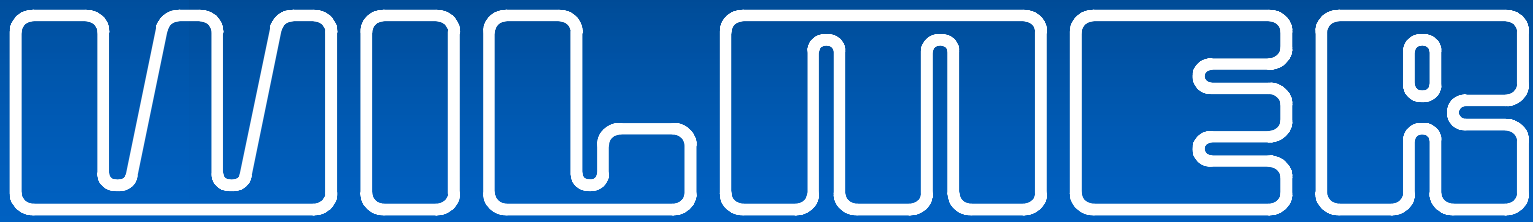

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