Pneumatic actuators

- Artificial Muscles (McKibben actuators)
- Soft Pneumatic Actuators (SPA)
McKibben actuator design parameters

Ushijima (2013)
McKibben actuator design parameters

a

b

Braided mesh woven sleeve

Internal rubber tube

c

\[ L \]

\[ \gamma \]

\[ b \]

\[ n\pi D \]

\[ t_k \]

\[ t_R \]

\[ \sigma_{\theta,\text{rub}} \]

\[ \sigma_{x,\text{rub}} \]

\[ T \]

\[ T_{\theta} \]

\[ \theta(y) \]

\[ l \]

\[ l_x \]

\[ l_y \]

\[ a \]

\[ a_c \]

\[ l_0 \]
Pneumatic actuators

- Artificial Muscles
- Soft Pneumatic Actuators (SPA)
Soft Pneumatic Actuators Overview

- Soft Pneumatic Actuator simplifies physical interaction with the environment
  → Back-drivable with high force output
- ‘Bonus’ properties include:
  - Easy fabrication and customizability
  - Lightweight, bio-compatible
  - Doubles as a safety mechanism
Mechanics for Soft Robotics

- *Soft actuators for rehabilitation and assistive motion* – soft hands, gloves, arms, legs, feet, heart, spine, trunk carapace
- Mechanics employed to model actuators – enable efficient design
- Computational models not at pace with devices – Rare examples in literature of studies for modeling, optimization - e.g. soft heart (Harvard)
- Device-scale models for full exoskeletons or gloves/assistive hands potentially very useful for replicating human functionalities
Expanding the area of application

Power ($\propto$ stiffness)

- Portable Robots (Flyer, Crawler, ...)
- Power assistive devices

Size ($\propto$ compliance)

- Small-scale manipulation
- SPAs
- Safety mechanisms

- $\sim 10^{-3}$ m (insects)
- $\sim 10^{-2}$ m (birds, rats)
- $\sim 10^{-1}$ m (cats, primates, human body parts)
- $\sim 1$ m (larger mammals, human whole body)
## Fabrication Process and Types

<table>
<thead>
<tr>
<th>Linear SPA</th>
<th>Bending SPA</th>
<th>Rotary SPA</th>
<th>Folding SPA</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Image A" /></td>
<td><img src="image2" alt="Image G" /></td>
<td><img src="image3" alt="Image N" /></td>
<td><img src="image4" alt="Image U" /></td>
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<tr>
<td><img src="image5" alt="Image B" /></td>
<td><img src="image6" alt="Image H" /></td>
<td><img src="image7" alt="Image M" /></td>
<td><img src="image8" alt="Image V" /></td>
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<tr>
<td><img src="image9" alt="Image C" /></td>
<td><img src="image10" alt="Image I" /></td>
<td><img src="image11" alt="Image L" /></td>
<td><img src="image12" alt="Image W" /></td>
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<tr>
<td><img src="image13" alt="Image D" /></td>
<td><img src="image14" alt="Image J" /></td>
<td><img src="image15" alt="Image F" /></td>
<td><img src="image16" alt="Image X" /></td>
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<tr>
<td><img src="image17" alt="Image E" /></td>
<td><img src="image18" alt="Image K" /></td>
<td><img src="image19" alt="Image C" /></td>
<td><img src="image20" alt="Image Y" /></td>
</tr>
</tbody>
</table>

1 cm

### SPA Skin

- **α**
- **β**
### Soft Pneumatic Actuators (SPAs)

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<th>Rotary SPA</th>
<th>Folding SPA</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Applied pressure</strong></td>
<td>30 kPa</td>
<td>50 kPa</td>
<td>30 kPa</td>
<td>25 kPa</td>
</tr>
<tr>
<td><strong>Block force/torque</strong></td>
<td>4.3 N</td>
<td>1.2 N</td>
<td>0.75 Nm</td>
<td>7.53 Nmm</td>
</tr>
<tr>
<td><strong>Range of motion</strong></td>
<td>0 - 33.9 mm</td>
<td>0 - 287.5°</td>
<td>0 - 44.9°</td>
<td>0 - 147.5°</td>
</tr>
<tr>
<td><strong>30% max disp. in</strong></td>
<td>0.77 s</td>
<td>0.74 s</td>
<td>0.18 s</td>
<td>0.06 s</td>
</tr>
</tbody>
</table>
SPA Mobile Robots

Soft-autonomous earthworm – MIT - USA

GoQbot – Tufts- USA

Multigait Soft Robot – Harvard - USA

Micro-walking robot – Okayama Univ - Japan
SPA Crawler for Disaster Mitigation

- Soft Pneumatic Actuator based Robot
- High Power to Force Ratio
- Inherent compliance and adaptation to the environment
- Redundant and modular architecture
Modelling of SPA

- A SPA Design tool based on FEA.
  - Provides an in-depth understanding of the material properties.
  - Allows to explore the parameter space more efficiently to generate optimized SPAs for any applications.
Theory - Volume flow rate ($q$) of air

$$q = VA = \sqrt{\frac{2 \cdot \Delta P \cdot \rho A^2 D}{f_D L}} \rightarrow q \propto D^{2.5}$$

Darcy-Weisbach

Weymouth

Panhandle

Experiment

$speed \propto D^{3.0}$
Theory – Instability during Balloon Inflation

In our case, prediction:

\[
p_{\text{crit}} = \frac{p}{2\mu t} \]

Actual:

\[
p_{\text{crit}} = 15\sim25 \text{ kPa}, \quad \lambda_{\text{crit}} < 1.25
\]

\[
\lambda_{\text{crit}} = 1.45
\] (Assuming \( r \gg t \))
FEM simulations for soft actuators

Fig 1. Finite element simulation results for soft fluidic actuators in bending and extension motion. These actuators comprise of an elastomer core with multiple air chambers in (a) and (d), and a single core reinforced with a shell structure of stiffer material in (b) and (c).
FEM–based Design tool for soft actuators

Experimental stress-strain data fitting to a hyperelastic and/or viscoelastic stress-strain constitutive law.

- SPA Geometry: number and form of chambers, max and min wall thickness, etc.
- SPA type: Bending or Linear
- Material experimental data

Geometry optimization through iterative design simulation.

Optimized SPA designs
Looking Ahead: Mechanics for Soft Robotics

Current Methodology

- Design a new Actuator
  - What material to use?
  - How to manufacture?
  - Test actuator for performance
  - Performance comparison with other actuator prototypes

Proposed New Methodology

- Target a specific assistive application
  - Filter mechanical design criterion based on application
  - Investigate targeted behavior, choose appropriate material, geometry through device modeling and preliminary experimentation
  - Fabricate actuators according to guidelines, combine actuators into device
  - Validate device performance with model

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Current Methodology

Proposed New Methodology
Soft Actuators: Existing Technologies

Pneumatic Artificial Muscles (PAMs)

Pneu-Nets Bending Actuators

Fiber-Reinforced Pneumatic Actuators

Shape Deposition Manufacturing (SDM) Fingers

Multi-Module Variable Stiffness Manipulator

Dielectric Elastomer Actuators
Soft Pneumatic Actuators (SPA)

Types of SPA:
- Linear
- Bending
- Rotary
- Skin-like

Applications:
1. Trunk Carapace with Artificial Muscle Packs for Human Gait Assistance
2. Rodent Exoskeleton
3. Disaster Mitigation Legged Robot
4. Vibro-tactile Feedback

Prototype of SPA-skin

EPFL École Polytechnique Fédérale de Lausanne
Reconfigurable Robotics Lab
Swiss National Centre of Competence in Research
Modeling for Soft Pneumatic Actuators

- Predict motion and force profiles
- Design better actuators

Bending Actuator

Linear Actuator

Predictions for Motion and Force using FEA
- Soft actuator core reinforced with thin shell of much stiffer material
- Pre-defined pattern on shell produces desired motion trajectory upon core inflation
- Shell interchangeable from actuator to actuator
Shell-reinforced Soft Pneumatic Actuators

MOTIVATION
• Manufacturable
• Repeatable
• More robust
• Better performance

A) Balloon without frame

B) Balloon with bending frame

C) Balloon with linear frame

unstretchable layer

Bending Actuator

Linear Actuator

Ecole Polytechnique Fédérale de Lausanne
Reconfigurable Robotics Lab
Swiss National Centre of Competence in Research
Actuator Fabrication

1. Elastomer core formed in single-step molding process (single air chamber)
   1) Silicone poured, degassed & cured into mold to form the balloon
   2) Balloon with plug taken out of mold
   3) Aluminium plug peeled out of balloon
   4) End caps & tubing glued using Silpoxy™ (smooth-on.com)

2. Reinforcement shell pattern cut with CO₂ laser, depending on motion required

- Use of adhesives (source of potential mis-alignment, mechanical non-uniformity and failure) minimized
- Repeatability and robustness due to use of precisely patterned shell as opposed to manual fiber braiding
- Over inflation of core constrained to prevent bursting at high pressures

3. Shell slid over core, end caps attached with screws to form complete actuator assembly
Mechanical Testing

1. Core Material: Ecoflex 30 (Silicone)
2. Shell Material: PET (Thermoplastic)

- Uniaxial Tension Test (Shell, Core)
- Planar Tension Test (Core)
- Stress Relaxation Test (Core: Viscoelasticity)
- Cyclic Loading Test (Core: Mullins Effect)
FEM Model

- **Software**: Abaqus/Standard
- **Analysis**: Quasi-static (improves convergence at higher pressures; Rayleigh damping to keep kinetic effects to a minimum)
- **Elements**
  - Actuator: Solid linear hexahedral hybrid elements (C3D8RH)
  - Shell: Solid linear quadrilateral elements (S4R)
- **Applied Constraints**
  - Friction between shell and actuator body; Penalty formulation using finite coefficient of friction with isotropic directionality
  - Tie constraint for bending actuator to simulate adhesive contact at narrow un-stretchable layer
- **Boundary Conditions**
  - Fixed air inlet surface
  - Internal pressure at all air chamber surfaces; Linear ramp-up from 0 – 50 kPa
  - Half-symmetry
  - Test-specific BCs (e.g. encastre at distal end for blocked force)
- **Mesh**
  - Biased meshing with highest density of elements at un-stretchable layer (bending actuators) and at shell slit corners (linear actuators)
- **Convergence Testing**
  - Solution convergence with as few as 3670 nodes; tested upto a million nodes
Model Geometry and Constraints

Pre-defined Guiding Pattern On Stiff Shell

Assembly on Soft Ecoflex Core

Slip permitted along circumference

Tie constraint on thin layer for bending actuators
Hyperelastic Model Fit

- Linear models such as Mooney-Rivlin, Neo-Hookean not appropriate to capture large range of strains experienced (> 500%)
- Models such as Polynomial, Yeoh, Ogden, Arruda-Boyce compared for best fit to experimental data
- **Ogden model best fit for chosen material: Ecoflex-30™**
- Defined by a stored energy function, $W$:
  
  $$
  U = f(l_1, l_2, l_3)
  $$

  - $U$ = Strain energy density or stored energy per unit volume
  - $l_1, l_2 and l_3$ = The three strain invariants of the green deformation tensor
  - $\lambda_1, \lambda_2 and \lambda_3$ = Principle extension ratios

  $$
  U = \sum_{i=1}^N \frac{2\mu_{\downarrow i}}{\alpha_{\downarrow i}} + \frac{2\lambda_{\downarrow 1} \alpha_{\downarrow i} + \lambda_{\downarrow 2}}{\alpha_{\downarrow i}} + \frac{\lambda_{\downarrow 3} \alpha_{\downarrow i} - 3}{\alpha_{\downarrow i}} + \sum_{i=1}^N \frac{1}{D_{\downarrow i}} (J_{\downarrow i} - 1)^2
  $$
Hyperelastic Model Fit

Ogden Model (3-term)

Ogden Model (6-term)

Arruda Boyce Model

Polynomial Model
Hyperelastic Parameter Optimization

Tune hyperelastic parameters to iterate towards desired actuator behavior (Nelder-Mead Optimization Loop)
Hyperelastic Model Fit

Arruda Boyce Model Fit

6-term Ogden Model Fit

Polynomial Model Fit
Viscoelastic Effects

- Applications mostly at room temperature
- Stress relaxation testing
- Prony series fit
  - $G$ : shear modulus
  - $K$ : bulk modulus
  - $G_0$ : Instantaneous value of modulus immediately after loading
  - $G_i$ and $\tau_i^G$ are fitting parameters
- **Relaxation less than 3% - Effects minimal**

$$G(t) = G_0 - \sum_{i=1}^{N} G_i \left[ 1 - e^{-t/\tau_i^G} \right]$$

$$K(t) = K_0 - \sum_{i=1}^{N} K_i \left[ 1 - e^{-t/\tau_i^K} \right]$$
Bending Actuators : Free Bending
Comparison of FEM and experiments

Stress distribution within actuator more uniform with increase in cuts on shell surface - Less bloating
of air chamber permitted due to larger surface area for expansion at the contact interface

Mention max. stress reached
Discussion on how stress mitigated with increasing cuts
Bending Actuators: Comparison of FEM and experiments

**Free Displacement Testing**

- Input pressure to obtain a given angle slightly decreases with increase in number of cuts on shell surface.
- Blocked torque tests in 2 steps:
  - only the proximal end of the actuator is fixed in all directions and the distal end is unconstrained. Pressure load required to take the actuator up to 45° is applied in this step.
  - the distal face and the end cap corresponding to that face are also fixed and the pressure load is then ramped up. The net reaction forces generated at the nodes on the distal face are summed up.
Bending Actuator – Stiffness Sweep for Shell
Free Bending Simulations

\[ E_{\text{shell}} = 1 \text{ GPa} \]
\[ E_{\text{shell}} = 0.5 \text{ GPa} \]
\[ E_{\text{shell}} = 0.25 \text{ GPa} \]
\[ E_{\text{shell}} = 0.05 \text{ GPa} \]
Bending Actuators: Free Bending Friction Sweep and Convergence Testing

- Friction coefficient sweep between 0.1 to 0.6
- Decrease in bending performance at increasing values of friction
- Unstable behavior at larger values of pressure at a low value of 0.1
- Nominal friction coefficient of 0.2 chosen
- Mesh convergence with <5000 nodes for both linear and bending actuators after bias
Biased Meshing for Convergence

- Finer Mesh in regions of rapidly changing stress
- Coarser Mesh

Without bias

With bias
Linear Actuator – Free Displacement

- Input Pressure = 50 kPa
- Max. Mises Stress = 58 MPa
- Elongation = 2.15X
- Stress concentration at all frame notches

Initial length = 40 mm
Final length = 86 mm
• Input Pressure = 50 kPa; Max Stress = 30 MPa
• Elongation = 2.45X
• Max. stress in frame nearly halved by increasing cuts by 50%
Linear Actuator – Blocked Force Simulations

Actuators with lower number of cuts on shell surface resist blocked force testing without buckling at higher pressures.
Linear Actuators:
Comparison of FEM and experiments

- The blocked force tests modeled with both end caps and end faces of the actuator fixed in all directions, and applying the pressure load with ramp increment. The net reaction forces generated at the nodes on the distal face are summed up to obtain the blocked force generated.
- Actuators with lower number of cuts on shell surface resist blocked force testing without buckling at higher pressures, since larger surface area of the air chamber is constrained in this case.
Conclusions and Future Work

- Novel, robust, manufacturable design for soft actuators presented, with application in soft robotic systems
- Optimal design of actuators developed with the help of FEM simulations
- Complex, non-linear mechanical behavior of silicone materials captured accurately with help of optimized hyperelastic model fit
- Future work – Model at system level