Comparison of various vibration motors for wearable devices

<table>
<thead>
<tr>
<th></th>
<th>C2</th>
<th>Haptuator</th>
<th>Tactaid</th>
<th>ERM pancake</th>
<th>ERM cylinder</th>
<th>Eskin Actuator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min. Size</td>
<td>D: 30 mm(\uparrow) h: 8 mm(\uparrow)</td>
<td>D: 14 mm(\uparrow) h: 29 mm(\uparrow)</td>
<td>w: 18.5 mm(\uparrow) d: 25.4 mm(\uparrow) h: 10 mm(\uparrow)</td>
<td>D: 10 mm(\uparrow) h: 3.6 mm(\uparrow)</td>
<td>D: 8.8 mm(\uparrow) h: 25 mm(\uparrow)</td>
<td>D: 6 mm(\uparrow) H: 3–4 mm(\uparrow)</td>
</tr>
<tr>
<td>Frequency</td>
<td>250 Hz(\uparrow)</td>
<td>50 Hz(\uparrow)</td>
<td>250 Hz(\uparrow)</td>
<td>175 Hz(\uparrow)</td>
<td>225 Hz(\uparrow)</td>
<td>Variable(\uparrow) (5–50 Hz)(\uparrow)</td>
</tr>
<tr>
<td>Weight</td>
<td>17 g(\uparrow)</td>
<td>15 g(\uparrow)</td>
<td>6.5 g(\uparrow)</td>
<td>2 g(\uparrow)</td>
<td>4.6 g(\uparrow)</td>
<td>2 g(with sensors)(\uparrow)</td>
</tr>
</tbody>
</table>
Concept of SPA-skin

- Wearable device
- Distributed sensing and actuation
- Input & output device
Concept of SPA-skin

Wearable device

Distributed sensing & actuation

Input & Output device

Actuation layer

Sensing layer Detects external load incl. vibration

1st module
2nd module
3rd module
4th module

10mm

Reconfigurable Robotics Lab.

Suh & Paik (2014)
Suh & Paik (2014)
Dynamic response

In collaboration with Lacour group
Vibratory SPA skin for tactile feedback

Prototype of the “soft tactile feedback skin” and functional schematics (Paik + Millan, unpublished)
Applications:
Mobile robot, Crawler

Open Loop
4x speed, 180mm/min
— 10mm

Reconfigurable Robotics Lab
École Polytechnique Fédérale de Lausanne
Applications:
Trunk Neuroprosthesis for Paralyzed rats

- Harnessing vest for test rat
- Anchored back for the weight support
Applications:

Trunk Neuroprosthesis for Paralyzed rats

In collaboration w/ Courtine group

multi-compartmental full contact prosthesis for hind leg re-education and lower back support

Lower back support during bipedal exercise → selective activation

Hind leg re-education via alternatively activated suit regions
Past progress recapitulation
The control system

- Rat Exoskeleton
- Force
- Pressure sensors
- Regulator
- Valves
- Valve driver
- Signal output and DAQ
- Controller
- Computer

Swiss National Centre of Competence in Research
## Current prototype

<table>
<thead>
<tr>
<th>General</th>
<th>Current Choice</th>
<th>Remarks</th>
</tr>
</thead>
</table>
|         | • Two passive arms attached to the backrest of the weight-support system | • Lightweight (< 100 grams)  
• Compact  
• Tethered |

<table>
<thead>
<tr>
<th>Actuator</th>
<th>Current Choice</th>
<th>Remarks</th>
</tr>
</thead>
</table>
|          | • Pre-bent bending soft pneumatic actuator (SPA)  
• 1-DoF frame attachment | • Sufficient force output  
• Up to 5 Hz actuation  
• Highly back-drivable  
• Lightweight (<10 grams)  
• *Promotes physical interaction* |

<table>
<thead>
<tr>
<th>Coupling</th>
<th>Current Choice</th>
<th>Remarks</th>
</tr>
</thead>
</table>
|          | • Bone pins (x2) on the femur bone  
• Optional pins (x2) on the pelvis  
• Magnet attachment to the actuator | • Complicates animal preparation  
• Invasive  
• Location/orientation varies  
• But it’s the *only option to ensure robust mechanical coupling* |

<table>
<thead>
<tr>
<th>Control</th>
<th>Current Choice</th>
<th>Remarks</th>
</tr>
</thead>
</table>
|         | • Pressure regulation  
• Valve operation (on/off)  
• Open-loop | • Fully autonomous  
• Requires external sources of power/pressure sources |

*Ready for the next stage: Address the “quality” of interaction between the machine and the animal*
• G-lab system provides $\theta(t)$
• RRL system turns ON the SPA just before $\theta_1$ i.e. ON during stance only and turn OFF just before $\theta_2$

* “Center point” is updated at every gait cycle
** $\theta_1, \theta_2$: pre-defined
Juan Florez
Yun Seong Song
Lou ann Raymond
Yann Amouyal
Prof. M Silvestro
Prof. G Courtine
Soft-neuro exosuit for rodents

- Goal: the rodent exoskeleton developed in subproject 2.1 will be used to adjust leg assistance for training.
- Objective: the animal will follow a locomotor rehabilitation procedure enabled by the exosuit. Their locomotor performance will be compared with those of non-trained and manually trained rats.

(Paik + Courtine + Micera)
Soft-neuro exosuit for rodents
Results: Adaptive Controller for pneumatic actuator

Period adaptation **preliminary results** with and without the gait period adaptation. On the top, we see little change in the GRF due to the mismatch (large $\Delta P$) in the gait cycle between the exoskeleton and the subject. On the bottom, we see a **dynamic array of GRF** for each cycle as the subject and the exoskeleton cycles match (small $\Delta P$).
Soft-neuro exosuit for rodents

Results

• Compliant Interaction

Three different ellipsoidal trajectories measured in vivo at the ankle using motion capture system Vicon. The shape of the trajectories is modulated via a GUI in Labview by modifying the ellipse parameters (minor and major axis, angle of rotation, x and z offset values). The ankle is attracted to the trajectory allowing compliance in the interaction for safety purposes.

• Force Modulation

The modulation of the ground reaction force was achieved by modifying the parameters of the input ellipse (z offset value or the major axis value - here represented as the major vs minor axis ratio). The dashed line represent the theoretical ground reaction force.
Trunk carapace for humans

- **Goal:** To develop a trunk carapace to actively control multidimensional trunk movements with soft actuation and smart passive structures.

- **Objective:** to translate previous achievements in animal models into a robot interface that provides optimal assistance to trunk movements during rehabilitation in humans.

Strategic placement of distributed soft actuator modules to provide assistance to contralateral, lean, and flexion/extension of the trunk. (5 active DoF)

Active module concept for trunk support and modulation for humans.
Trunk carapace for humans (unpublished)

• Biomimetic Approach:
  Mimic postural muscle groups for assistance and control of trunk movements.
• For example:
  – Erector Spinae: runs parallel with the spinae to extend vertebral column, produces erect posture and allows the spine to flex from side to side.

<table>
<thead>
<tr>
<th>Module Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions (WxLxT)</td>
<td>86x140x20 mm</td>
</tr>
<tr>
<td>Weight</td>
<td>170 g</td>
</tr>
<tr>
<td>Pressure range</td>
<td>0-2 Bar</td>
</tr>
<tr>
<td>Max Force</td>
<td>100 N</td>
</tr>
<tr>
<td>Frequency Range</td>
<td>&lt; 1Hz</td>
</tr>
<tr>
<td>Longitudinal Stiffness</td>
<td>≈ 7500 N/m (vs 5000 N/m when OFF)</td>
</tr>
<tr>
<td>Bending Stiffness</td>
<td>≈ 200 N/m</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>I.D. (mm)</th>
<th>O.D. (mm)</th>
<th>length (mm)</th>
<th>weight (g)</th>
<th>theoretical force</th>
<th>Actuating dir</th>
</tr>
</thead>
<tbody>
<tr>
<td>FESTO pneumatic cylinder</td>
<td>12</td>
<td>20</td>
<td>158</td>
<td>95</td>
<td>61 N @ 6 bar</td>
<td>tension</td>
</tr>
<tr>
<td>Single SPA</td>
<td>12</td>
<td>16</td>
<td>140</td>
<td>30</td>
<td>25 N @ 2 bar</td>
<td>tension</td>
</tr>
<tr>
<td>FESTO Pneumatic muscle</td>
<td>10</td>
<td>20</td>
<td>40-600</td>
<td>75</td>
<td>630 N @ 6 bar</td>
<td>contraction</td>
</tr>
</tbody>
</table>
Muscle groups simulated by the SPA modules (unpublished):

- Rectus abdominis: enables the tilt of the pelvis and the curvature of the lower spine.
- Actively modulating surface stiffness.

Contractile muscle groups are functionally simulated by SPA modules. We have 2 modules: bending and linear

<table>
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</tr>
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<tbody>
<tr>
<td>Dimensions (WxLxT)</td>
<td>86x140x20 mm</td>
</tr>
<tr>
<td>Weight</td>
<td>180 g</td>
</tr>
<tr>
<td>Pressure range</td>
<td>0-2 Bar</td>
</tr>
<tr>
<td>Max Bending Force</td>
<td>12 N</td>
</tr>
<tr>
<td>Frequency Range</td>
<td>&lt; 1Hz</td>
</tr>
<tr>
<td>Bending Stiffness*</td>
<td>≈ 950 N/m @ 2Bar</td>
</tr>
<tr>
<td></td>
<td>(≈ 400 N/m @ 0.5Bar)</td>
</tr>
</tbody>
</table>
Stiffness variable joints

- Impedance control
- Material based joint stiffness control
Stiffness change

https://www.youtube.com/watch?v=Rna03IlJjf8

Stiffness change

M. McEnvoy (2014) “Thermoplastic variable stiffness composites with embedded, networked sensing, actuation, and control”

Brown (2010)“Universal robotic gripper based on the jamming of granular material.”
Stiffness change

Cianchetti (2015) "A bioinspired soft manipulator for minimally invasive surgery"
JSEL: Jamming Skin Enabled Locomotion

Figure 2. Jamming skin enabled locomotion (JSEL) topology both unactuated (2(a)) and actuated with a subset of the ills jammed(2(b)). Figure taken from.8
Fig. 11. Diagram of future jamming robot concept.

Variable Stiffness Fabrics with Embedded Shape Memory Materials for Wearable Applications

Artificial Muscles from Fishing Line and Sewing Thread

Fig. 1. Muscle and precursor structures using nylon 6,6 monofilament sewing thread. Optical images of (A) a nontwisted 300-μm-diameter fiber; (B) the fiber of (A) after coiling by twist insertion; (C) a two-ply muscle formed from the coil in (B); (D) a braid formed from 32 two-ply, coiled, 102-μm-diameter fibers produced as in (C); (E) a 1.55-mm-diameter coil formed by inserting twist in the fiber of (A), coiling it around a mandrel, and then thermally annealing the structure; and (F) helically wrapping the fiber of (A) with a forest-drawn CNT sheet and scanning electron microscope images of a CNT-wrapped, 76-μm-diameter nylon 6,6 monofilament (G) before and (H) after coiling by twist insertion.
Fig. 4. Mechanism and applications for coiled polymer muscles. Hydrothermal actuation of a coiled 860-μm-diameter nylon 6 fishing line lifting a 500-g load by 12% when switched at 0.2 Hz between (A) ~25°C water (dyed blue) and (B) 95°C water (dyed red). (C) Calculated temperature dependence of tensile actuation (dashed lines) compared to experimental results (using an applied stress of 0.2 Hz, solid black and blue lines) for coiled data in the inset, which was then used to predict tensile actuation for the other coiled fibers. (D and E) Schematic illustration of the mechanism by which torsional fiber actuation drives large-stroke tensile actuation for (D) heterochiral and (E) homochiral coiled fibers. (F) Measured tensile actuation versus fiber bias angle for coiled, 860-μm-diameter nylon 6 muscles actuated between 25° and 95°C. (G) Typical photo of a high-activity fiber.
McKibben artificial muscle using shape-memory polymer


Fig. 5. Prototype of newly developed actuator with SMP.
Variable Stiffness Joints

→ under-actuated mechanism
An Under Actuated Robotic Arm with Adjustable Stiffness Joints

Amir Firouzeh, Jamie Paik
Reconfigurable Robotics Lab
Seyed Sina Mirrazavi Salehian, Aude Billard
Learning Algorithms and Systems Laboratory

The work was supported by:
Swiss National Center for Competence in Research in robotics
EU projects AlterEgo
Soft Sensors

- Material based
- Design based
Soft components: Soft Sensors

Principle: conductive ink /silicone, liquid metal sensors
Under strain, the effective conductive path ways are deformed.

Soft Sensors
Conductive thermoplastic elastomer

Soft Sensors
Conductive thermoplastic elastomer

Soft components: Soft Sensors

Liquid metal-based sensors

Conductive silicone based sensors

Carbon ink based sensors

PDMS micro-channeled sensor, 700um thick micro channel

Paik (2011)
Conductive silicone-based sensors
Carbon ink-based sensors
Soft components:

**Soft Sensors**

**Strain Sensing**

\[ \Delta R = \frac{\rho L}{wh} \left( \frac{2}{\lambda^2} - 1 \right) \]

**Pressure Sensing**

\[ \Delta R = \frac{\rho L}{wh} \left( \frac{1}{1 - 2(1 - \nu^2) \sigma p/E h} - 1 \right) \]

**Curvature Sensing**

\[ e_0 = \frac{(g+H)}{2R} \]

\[ e_0 = -\frac{(g+H)}{2R} \]
Stretchable electronics

• Stretches 300% of its initial length
Stretchable electronics


Paik, Kramer, Wood (2011)
Soft Sensors

- Material based
- Design based
Soft components:

Soft Sensors
Soft Sensors

Kim, et al. 'Epidermal electronics.' (2013)
Soft components:

Soft Sensors

- Ommatidia
- Compound Eyes
- Antennae
- Hairs
SoY

Soft components:

Soft Sensors

Floreano (2013)
Soft components:

Soft Sensors: discrete components

- polymer lenses
- low-reflective apertures
- glass substrate
- CMOS chip with photodetectors
- flexible printed circuit board
- electronics components in concavity

ALIGNED ASSEMBLY
WIRE BONDING
DICING OF COLUMNS

Floreano (2013)
Soft components:

Soft Sensors: discrete components

Acer & Paik (2015)
Soft components:

Soft Sensors: discrete components

Acer & Paik (2015)
Soft components:

Soft Sensors: discrete components

Acer & Paik (2015)
Soft Sensors by design
Effective section

$I_{\text{mesh}}/2$

Effective section counterpart

$F$

$I_{\text{mesh}}/4$
Soft Sensors by design
Hybrid soft sensors

Firouzeh & Paik (2015)
Applications

Neural signal sensing
- EEG
- MEA
- ECoG
- Cuff electrode
- LIFE electrode
- TIME electrode

Kinematic and EMG sensing

Kinematic and EMG, peripheral
Muscular stimulation

WEARABLE ROBOTICS

Courtine et al. (2013)
Toward the Future of Soft Robotics

- Soft Robots
  - Wearable Robots
  - Exploratory Robots
  - Co-Robots

- “Spin-offs”
  - Stretchable & Wearable Electronics
  - Artificial Muscles
  - Soft Microfluidics

- Commercial Markets
  - Personal Robotics
  - Medicine & Rehabilitation
  - Entertainment & Gaming
  - Surveying & Exploration

- Manufacturing
  - Soft Lithography
  - Roll-to-roll
  - 3D Printing

Authors:
- Majidi (2014)
- Conor (2013)
- Kasper (2013)
- Park (2013)
- Shea (2013), Ryser (2013)
Origami-based reconfigurable robots, Robogamis: Facial rehab robot and Crawler
Origami-based reconfigurable robots, Robogamis: Facial rehab robot and Crawler
Robogamis: origami robots with multi-modal locomotion
Wearable technology

- Sensing input
  - contact force
  - Contact location

- Output
  - Actuation / vibration
  - Thermal changes
  - Electric stimulation
Applications:
Robogamis for Facial Rehab
Applications: Robogamis for Facial Rehab

- Multi DoF Robogami to
  - Analyse: current status and progress
  - Measure: intensity of contraction, timing of the contraction in different muscles, tremor level in patients
  - Train: specific muscle groups (independently and simultaneously)
Applications: Endonasal Surgical Instrument

The scanned skull and the endonasal tool

The tool is manipulated to enter inside the skull from the nasal cavity

Collision detection throughout the toolpath.

The surgical simulator connected to the phantom surgery.
# Soft robotics

<table>
<thead>
<tr>
<th>Purpose</th>
<th>• New solutions for robots with heightened interactivity: compliancy toward environment &amp; task, safety, reconfigurability</th>
</tr>
</thead>
</table>
| Imperative components | • Soft actuators  
• Soft sensors  
• Controllable stiffness material / joints / solutions |
| Advantages | • Customizability  
• Cost  
• Flexible and stretchable for diverse surface applications |
| Challenges & goals for the immediate future | • Material and mechanical design are THE key (application specific with clear functional requirements)  
• Refinement of fabrication process  
• Integration and development of soft components  
• Need novel control methods and computational techniques  
• Need unique design and simulation tools |