Corso di Sistemi biomimetici

Perforation-type anchors inspired by skin ligament for robotic face covered with living skin

Michio Kawai, Minghao Nie, Haruka Oda, and Shoji Takeuchi

Politecnico di Torino

1859

Claudia D’Agostino

Torino, 26/02/2025

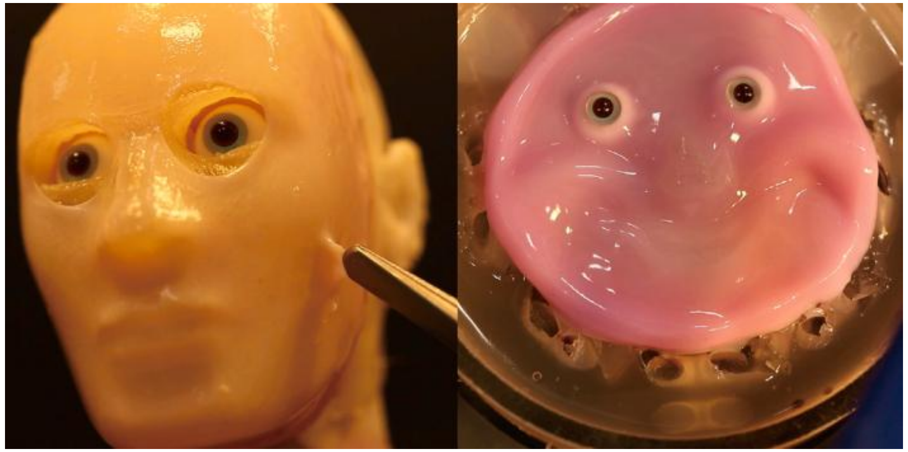
Overview: biomimetic artificial skin for robotics

Research Goal:

- Develop an **artificial skin attachment method** inspired by **human skin ligaments**
- Enable **stable integration of living skin** on robotic surfaces

Key Findings:

- **Plasma treatment** enhances collagen adhesion
- **Perforation-type anchors** improve skin fixation & prevent contraction
- **3D facial mold** covered with skin equivalent demonstrates feasibility
- Robotic face model **mimics natural expressions**



Biomimetic Approach:

- **Structural biomimicry** → Perforation-type anchors replicate skin ligament function
- **Functional biomimicry** → The skin model provides elasticity and mechanical properties similar to natural skin
- **Mechanical biomimicry** → Anchors allow dynamic facial expressions

- Integrates **biological materials** with **artificial structures**
- Allows **lifelike appearance & movement** of an artificial system
- **Potential applications** in robotics, regenerative medicine, and cosmetics

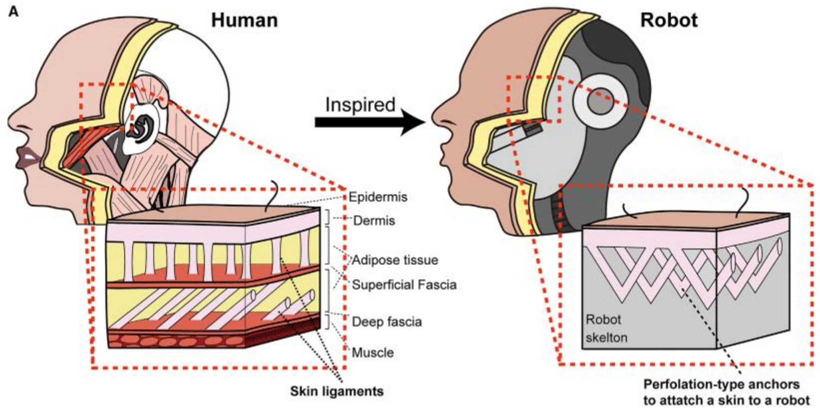
Robot skin materials overview

Current robotic skin goals:
- Mimic human skin functions: **tactile sensitivity, self-repair, perspiration, humanlike appearance**
- Cultured skin offers **better self-healing** than synthetic materials

Challenges in attaching cultured skin to robots:
- **3D skin equivalents** required for full coverage
- Existing methods (e.g., **shrink-molding**) lack stable attachment
- **Protrusion anchors** provide fixation but:

i. Bulky, disrupt smooth surfaces
ii. Difficult to use on concave structures

Innovation: Perforation-Type Anchors
- Inspired by **human skin ligaments**
- Uses **V-shaped perforations** to secure skin with cell-laden gel
- Enables stronger attachment & better mechanical integration



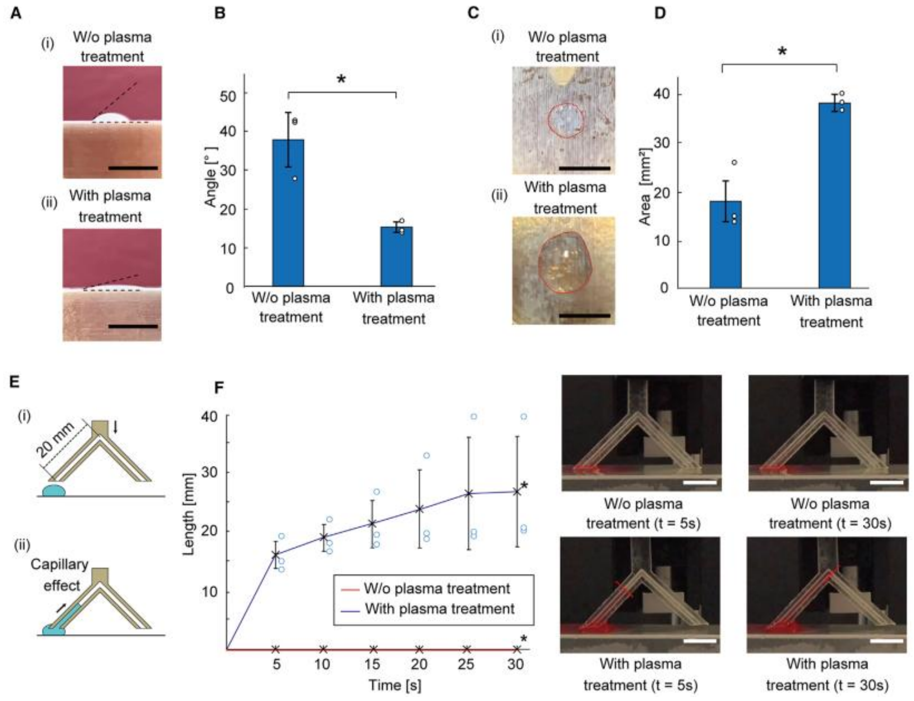
Plasma treatment for collagen penetration

Challenge:

- Collagen gel must **penetrate anchor interiors** for effective attachment
- Some anchors are **inaccessible**, making direct gel introduction difficult

Solution: Water-Vapor Plasma Treatment

- **Enhances surface hydrophilicity** → improves collagen infiltration
- Demonstrated through:
    - **Contact angle reduction:** Plasma-treated surfaces show better wettability
    - **Increased spreading area:** Collagen solution covers more surface
    - **Penetration test in 1 mm V-shaped anchors:** Plasma treatment significantly improves gel entry

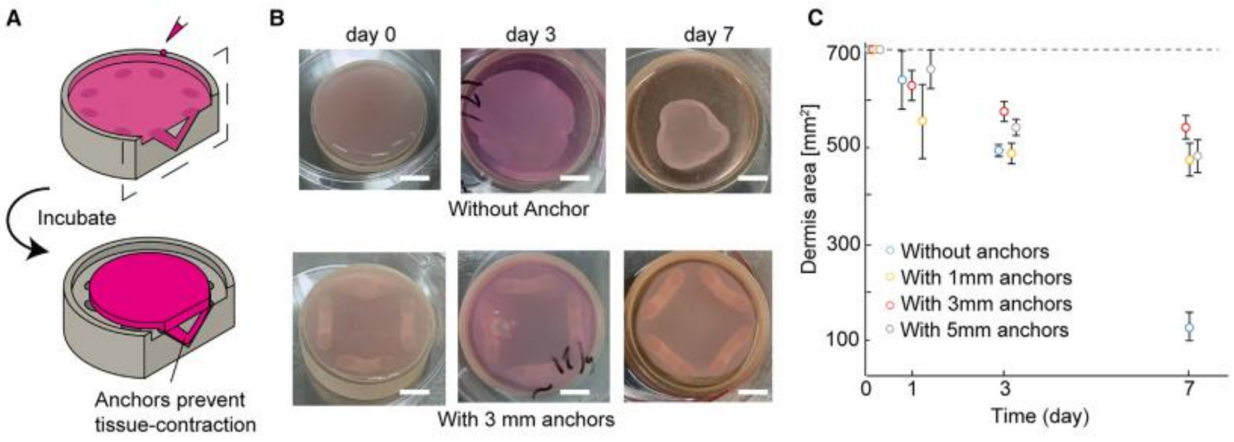


Evaluation dermis contraction prevention

Objective: Assess **anchor efficacy** in preventing skin shrinkage over **7 days**

Method:
- Compared contraction in samples **without anchors** vs. **1 mm, 3 mm, and 5 mm anchors**
- Measured skin area **immediately after gelation, after 3 days, and after 7 days**
- Used **high-viscosity (3.0 mg/mL) collagen solution** to test performance under challenging conditions

Results:
- **3-mm anchors** provided the **best resistance to contraction**
- **1 mm anchors** reduced shrinkage but less effectively
- **5 mm anchors** had a paradoxical effect, reducing post-contraction area due to excessive occupied space



Tensile tests: assessing mechanical strength

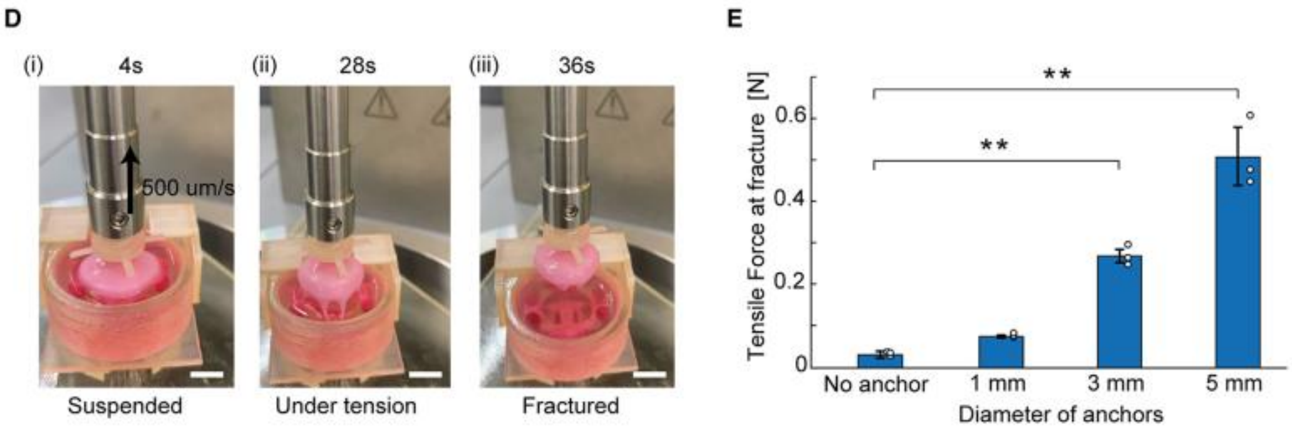
Objective: Evaluate **tensile strength** of dermis equivalent with perforation-type anchors

Method:

- **Collagen + NHDFs** gelated on dermis sheet holder
- **7-day incubation**, then tested using a **hooking jig & rheometer probe** (force sensors & motors)
- Measured **pulling force required to detach the dermis**

Results:

- **Larger anchor diameters → Higher tensile strength**
- Trade-off: Larger anchors increase fixation but **reduce available tissue area**



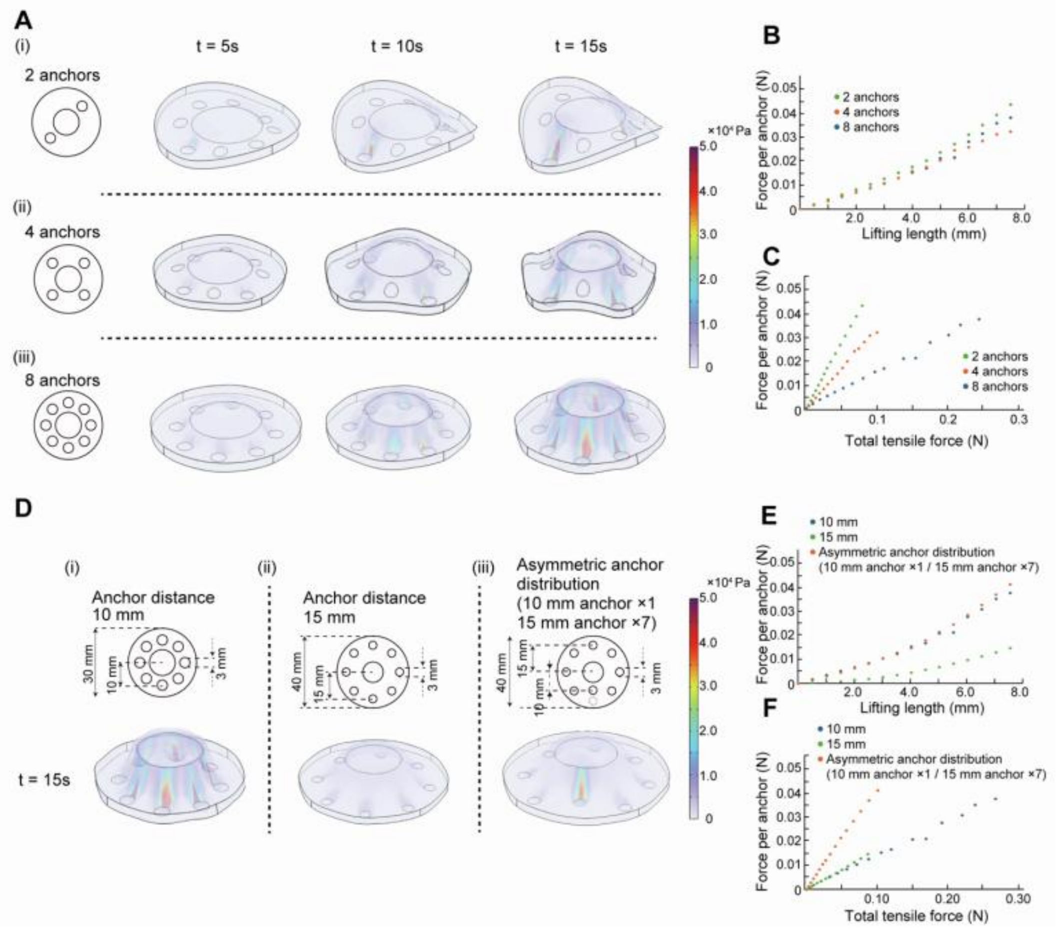
Optimization of anchor number & arrangement

Method: Finite Element Method (FEM) Simulation

- Simulated **first principal stress, total tensile force, and stress per anchor**
- Modeled **2-mm-thick hyperelastic dermis equivalent** with surface-fixed anchors
- Central part lifted at **500 mm/s**, analyzing force distribution

Key Findings:

- **More anchors → Higher resistance to tensile stress**
- Force per anchor varies even under equal external loads
- Anchor placement: **longer distances from force application → more displacement** under less force, higher rupture risk
- Trade-off:
  - **Lower density = More deformation tolerance**
  - **Higher density = Stronger adhesion but less flexibility**



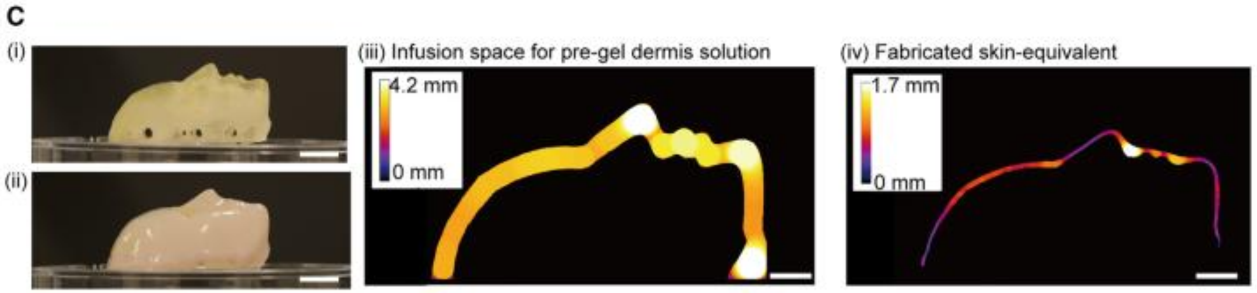
3D facial mold with skin equivalent

Mold Design:
- **3D facial device** equipped with **8 perforation-type anchors**
- Upper & lower molds create a cavity for **collagen solution molding**

Dermis Equivalent Formation:
- Pre-gel **dermis solution** (collagen, PBS, fibroblast medium, NHDFs) poured into mold
- **Incubated for 7 days** to crosslink collagen and allow tissue maturation

Epidermis Formation:
- Upper mold removed, **NHEKs** seeded (**1.0×10^7 cells/mL**) on dermis
- Cultured **3 days in medium** + **14 days at air-liquid interface**
- Whitish appearance indicates epidermis formation

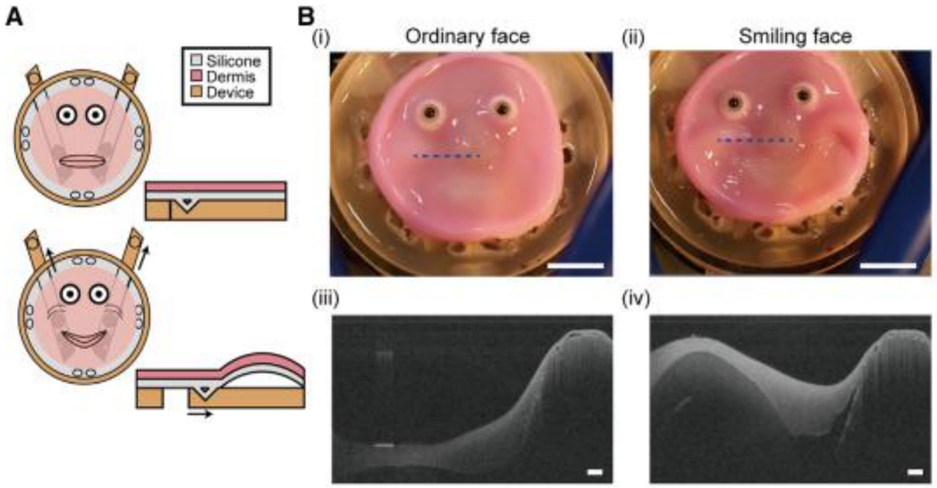
Final Skin Properties:
- Initial mold cavity thickness: 3.3 mm
- **Final skin thickness: 0.81 mm**
- Reduced **thickness variation** (SD): 0.50 mm → **0.33 mm**



Mimicking facial movements with perforation-type anchors

Biological Inspiration:
- **Mimetic muscles** (e.g., zygomaticus major) attach **to bone via retaining ligaments** and to skin **via skin ligaments**
- Smiling expression: Muscle contraction lifts mouth corners & cheeks

Robotic Face Model:
- **Dermis equivalent + silicone layer** attached to a **slider mechanism**
- Anchors for secure attachment:
  - **3-mm perforation anchors** → Fix **silicone & dermis layers**
  - **5-mm perforation anchors** → Secure **rod parts** for stronger actuation



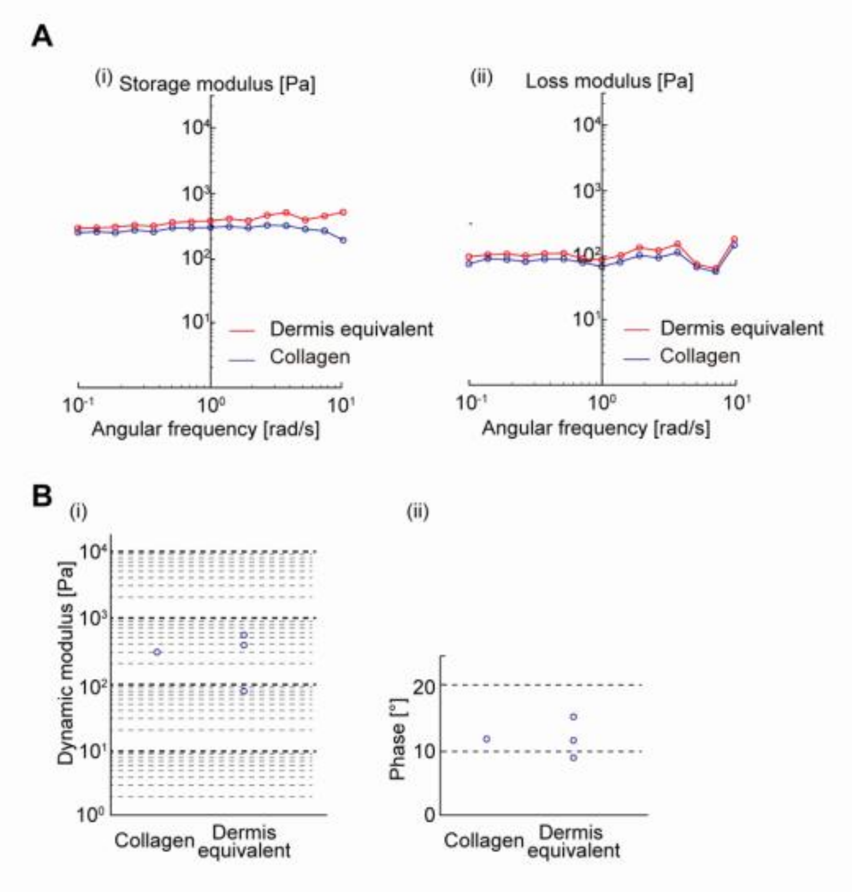
Key Takeaway:
- **Perforation-type anchors enable selective actuation**, mimicking in vivo facial muscle movements

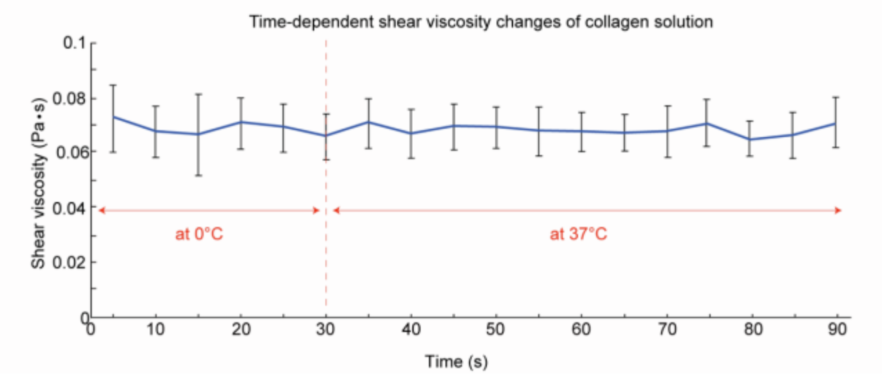
Mechanical characterization of dermis equivalent

Dynamic Mechanical Analysis (DMA): Dermis equivalent vs. acellular collagen comparison

Findings:

- Similar storage, loss, and dynamic moduli
- **Lower dynamic modulus** than in vivo dermis
- **No significant toughness increase** after **14-day NHDF cultivation**
- Suggests longer cultivation or improved conditions needed for collagen remodeling
- **Phase angle** comparable to in vivo dermis → similar viscoelastic behavior
- No notable increase in **shear viscosity** between 0°C and 37°C (~70 mPa·s)





Conclusions and future prospects

Enhancing Biomimicry:

- **Skin ligaments** are fine fibrous structures → **Microscale perforation anchors** could improve adhesion without punctures
- Replacing mechanical actuators with **cultured muscle** → Higher **biomimetic performance**

Optimizing Skin Thickness:

- **Variations in contraction forces** on concave vs. convex surfaces affect thickness
- Requires **better control of pre-gel dermis application**

Broader Applications:

- Wrinkle formation studies → Potential use in **cosmetic research**
- Expression modeling on chips → Applications in **cosmetics & orthopedic surgery**
- Understanding facial muscle-expressions correlation → Insights for **facial paralysis treatment**

Thank you
for your attention

Politecnico
di Torino

1859