Hongyu Yue

As a digital artist, researcher, and entrepreneur, I am committed to enhancing human perception and exploring its potential value in culture, health, and accessibility.

1 **E-Elasticity**
"An Electrotactile Method to Simulate Elasticity"
**HCI Research**

2 **Slip-Grip**
"An Electrotactile Method to Simulate Weight"
**HCI Research**

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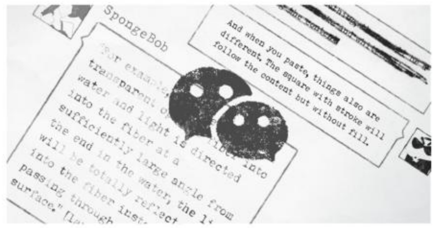
**Product**

4 **Urban Duo**
"A Stylized Animation Comparing Longchang Apartment and the City of Shanghai"
**Animation**

5 **ZenBelly**
"A Wearable Device for Maintaining Gut-Brain Axis Health"
**Product**

6 **Paper WeChat**
"Reimagining Social Media Through the Logic of Printed Media"
**APP**



7 **X-Garment**
"A Smart Garment for Muscle Compensation Recognition"
**Product**

## Research Paper

**Contribution**

***Co-First Author***
System Development; User Study Design and Execution; Paper Writing

**Collaborator**

Hongnan Lin, Fengyu Wang

**Keywords**

Electrotactile Technology, VR, Elasticity Perception

**Instructor**

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01

# E-Elasticity

### An Electrotactile Method to Simulate Elasticity

Accurately perceiving the elasticity of virtual objects is crucial in virtual reality; however, existing approaches are often cumbersome and impractical.

We introduce E-Elasticity, an electrotactile method for simulating elasticity in VR. The system determines whether the contact surface is in a static or slipping state based on the magnitude of stretching and the pinch force. It conveys this information through synchronized electrotactile and visual feedback, helping users understand and perceive the elasticity of the target object.

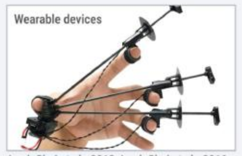
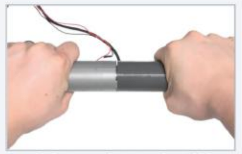
User studies have demonstrated that E-Elasticity enables participants to accurately distinguish predefined stiffness levels, offering a lightweight, efficient haptic solution for rendering elasticity in virtual environments.

*https://youtu.be/QkZUe8zimso*

*November 2024 – May 2025*
*Human–Computer Interaction Technology and Intelligent Information Processing Laboratory, ISCAS, Beijing, China*

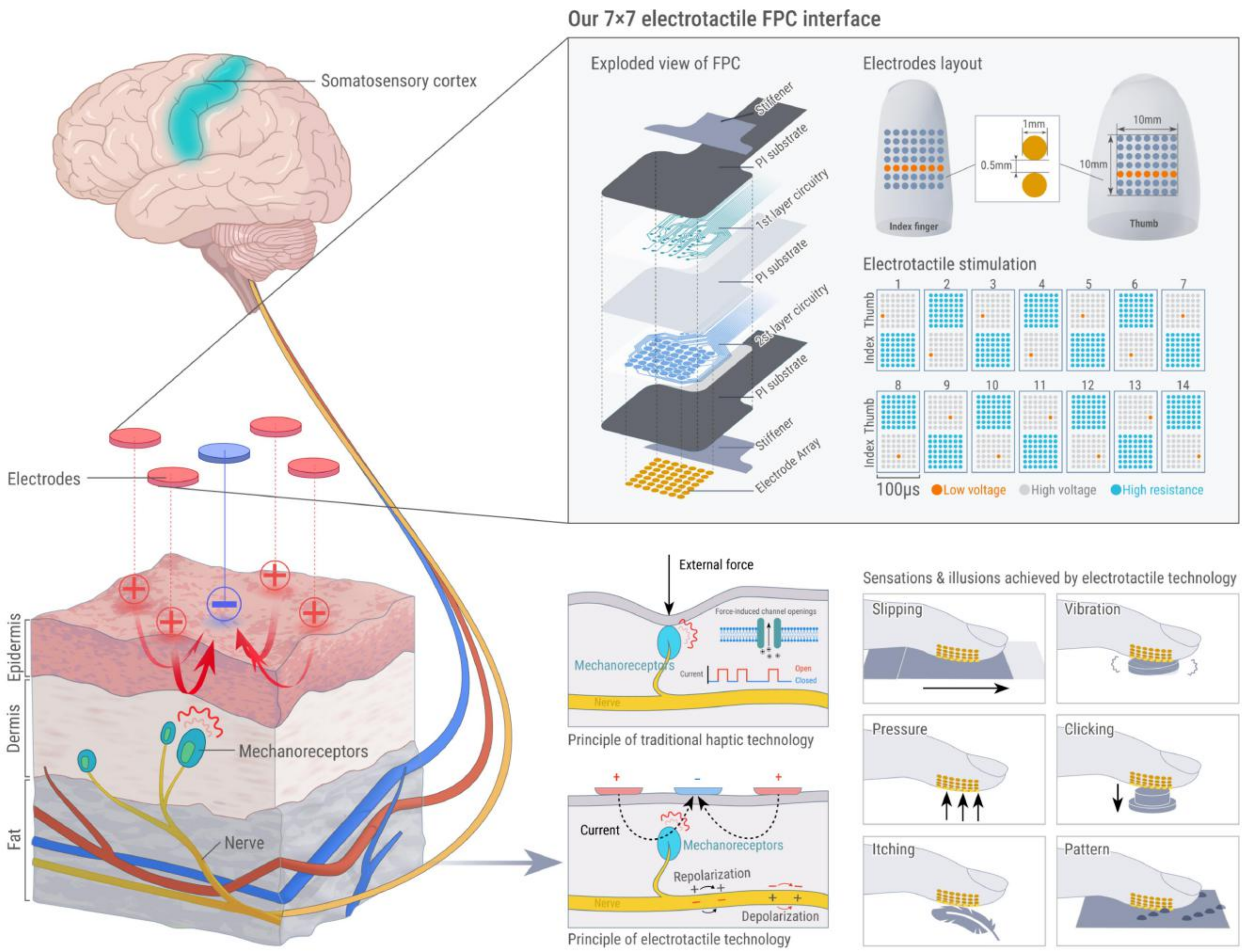
## Research Gap of Creating a Perception of Elasticity

Haptic feedback is essential for enhancing realism and performance in virtual and augmented reality, teleoperation, and VR-based training. **Elasticity, a fundamental property in object interaction, remains particularly challenging to render without mechanical actuation.** Previous research has used grounded devices, exoskeletons, or pseudo-haptics to simulate elasticity. But these approaches either lack realism or rely too heavily on vision. Slip and contact cues, which are critical to elasticity perception, remain underexplored.

| ❶ Force-displacement feedback | ❷ Tactile feedback | ❸ Pseudo-haptics | ❹ Vibrotactile |
|---|---|---|---|
| Grounded devices  Sensable technologies, 2007 | Skin stretch  Zhan Fan Quek et al., 2014; Samuel B. Schorr et al., 2017 |  |  |
| Wearable devices  Inrak Choi et al., 2018; Inrak Choi et al., 2016; Mike Sinclair et al., 2019; Hsin-Ruey Tsai et al., 2018 | Contact area  A. Bicchi et al., 2000; K Fujita et al., 2001; Yujie Tao et al., 2021 |  Takahiro Kawabe, 2020; Katrin Wolf et al., 2015; Arata Kokubun et al., 2013; Yannick Weiss et al., 2023; |  Seongkook Heo et al., 2019; Johan Kildal, 2010; Jaeyeon Lee et al., 2019; Seongkook Heo et al., 2016 |
| 👍 Highly realistic | 👍 Realistic | 👍 No haptic devices required | 👍 Accessible actuator |
| 👎 Large & complex | 👎 Complex | 👎 Occupying vision | 👎 Cannot simulate elasticity under large lateral deformations |

## Electrotactile Technology

**Electrotactile** is an emerging technology. It fabricates electrode arrays on thin, flexible printed circuits (FPCs), offering advantages such as **flexibility, thinness, light weight, and high precision**. Electrotactile devices directly generate local skin current that triggers neural potentials, which the brain interprets as tactile stimuli. By varying waveform, frequency, duration, or location, it can evoke sensations such as vibration, sliding, pressure, or button-clicking. We designed **two high-density 7×7 fingertip arrays for the index finger and thumb** to support subsequent electrotactile research.

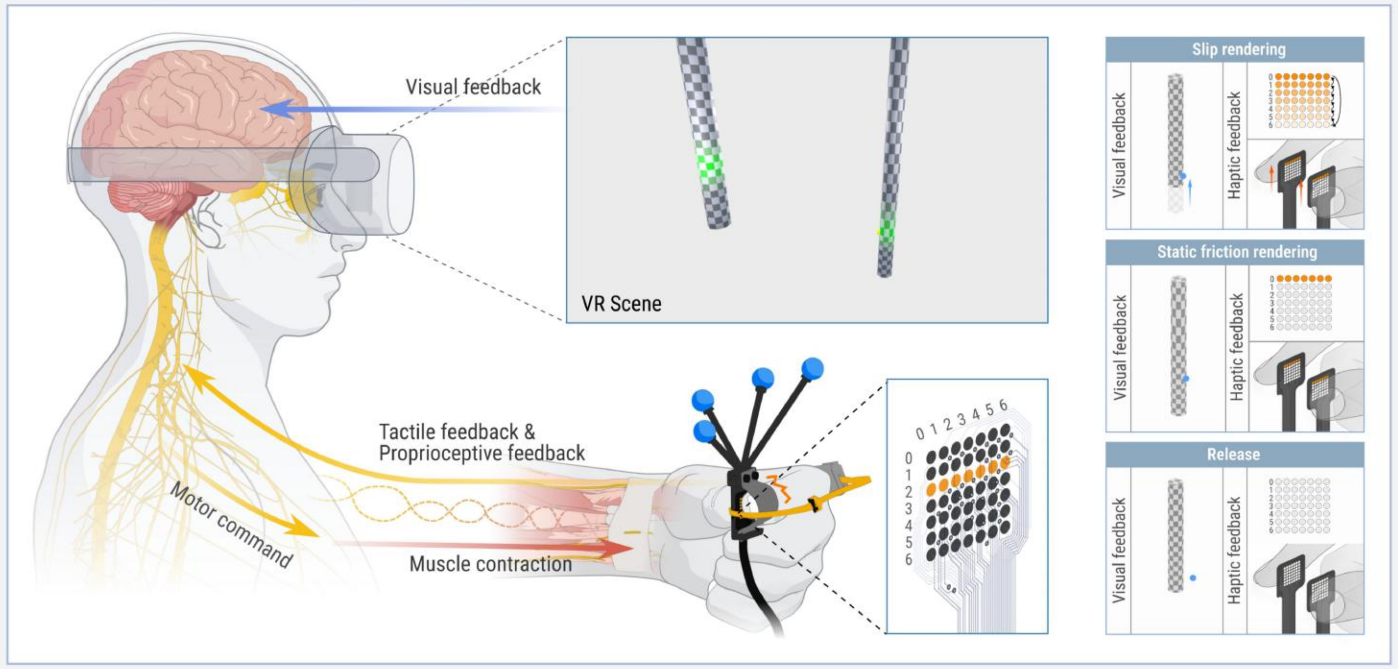



## E-Elasticity: An Electrotactile Method to Simulate Elasticity

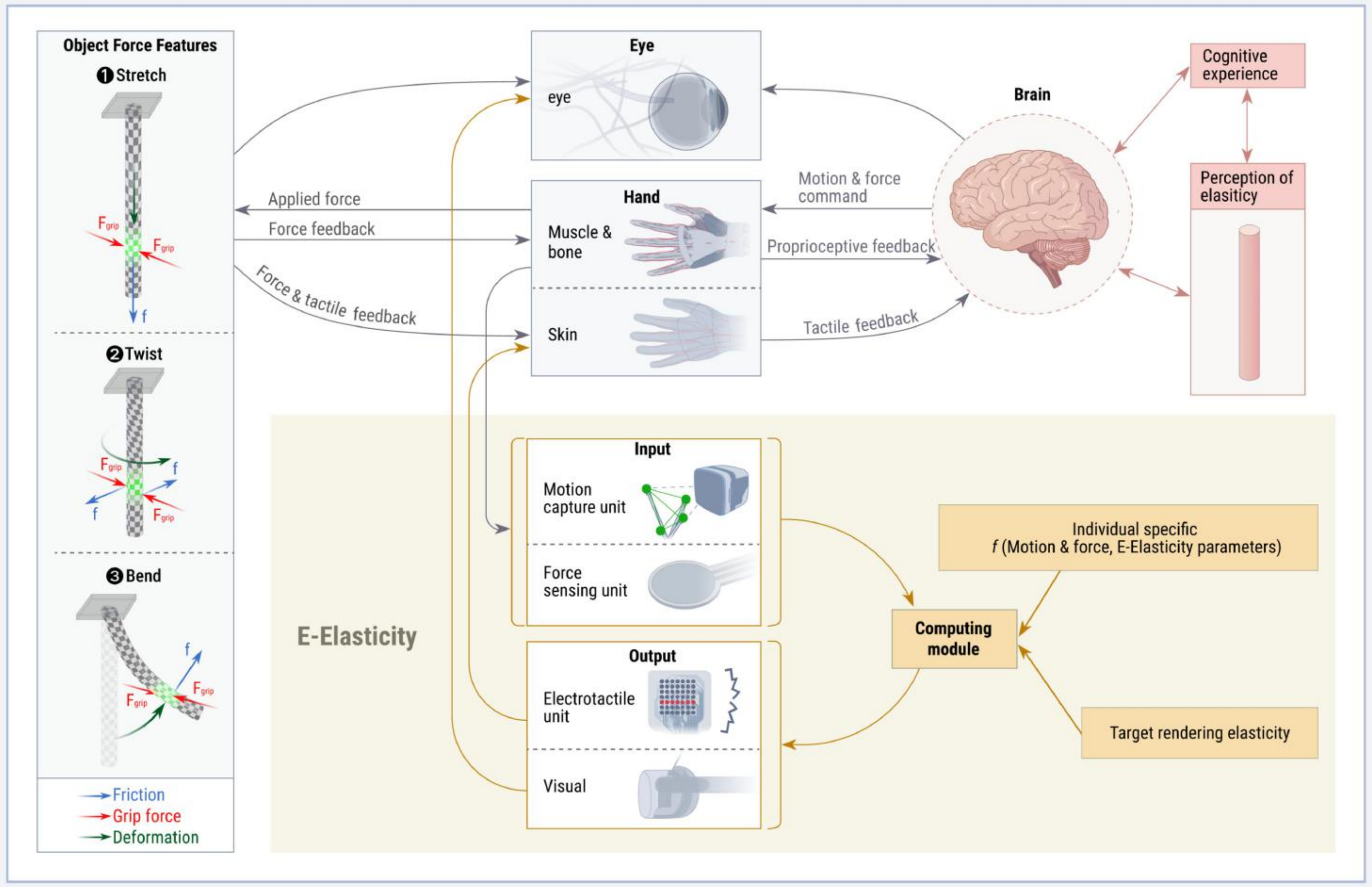
Human perception of elasticity depends on the relationship between the applied force and the resulting deformation. When stretching one end of an elastic cylinder, the normal force maintains the grip, the lateral force produces deformation, and the reaction force pushes back. To prevent slipping during stretching, the maximum friction generated by the grip force must exceed the lateral reaction force. For a given deformation, higher elasticity produces stronger reaction forces and therefore requires a greater normal grip force. The brain integrates tactile, proprioceptive, and visual cues to infer elasticity.

**We introduce E-Elasticity**, a method that simulates elasticity via electrotactile stimulation. The system continuously **monitors lateral motion and normal force, determines contact states (static friction/slip/release), and generates corresponding visual and electrotactile feedback to modulate the perceived elasticity.**

### Schematic diagram of E-Elasticity technology



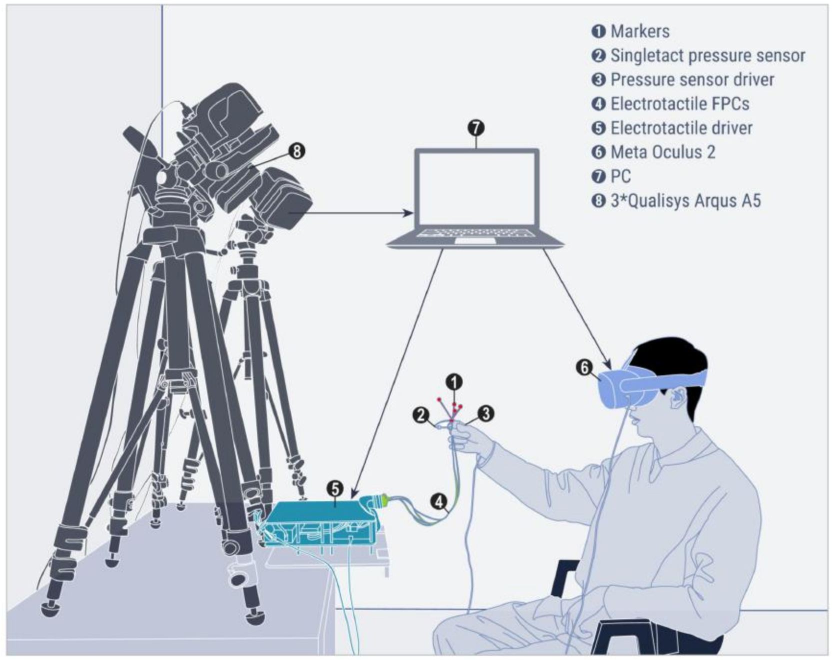

### How E-Elasticity modulates the perception of elasticity? — Motion-Electrotactile Coupling

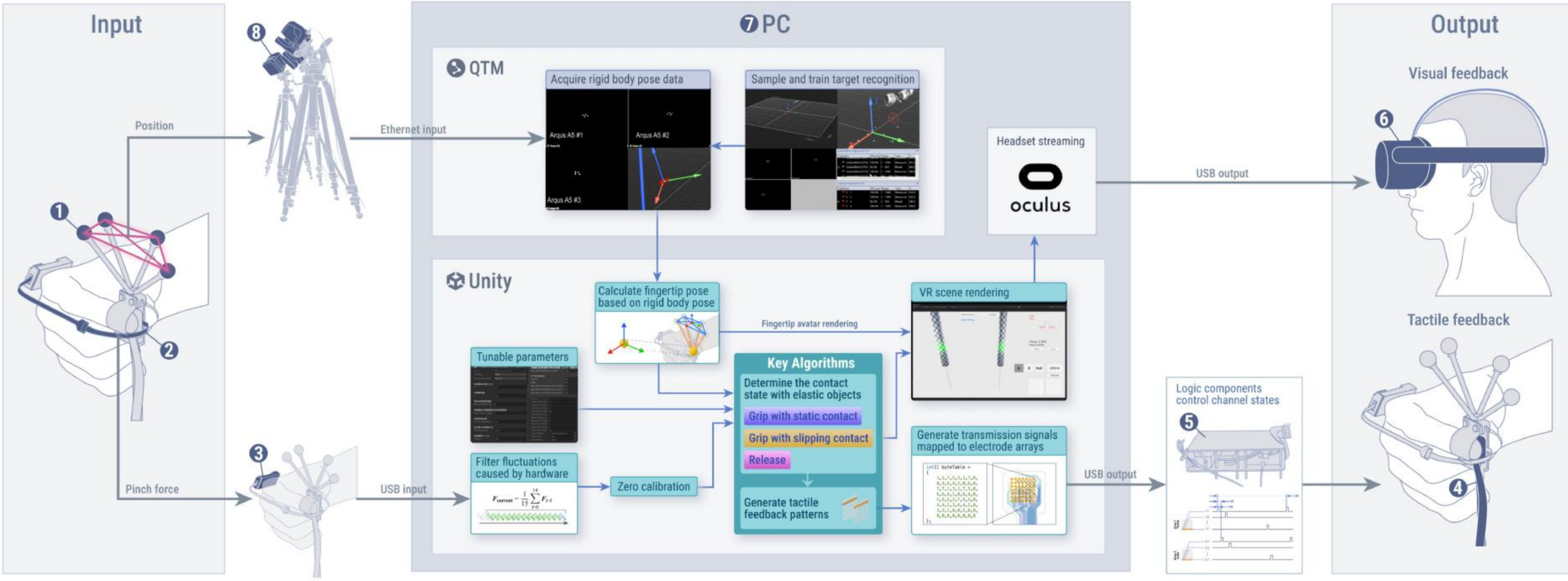


## ■ E-Elasticity System Design

The pinch force and fingertip position are transmitted to the computer in real time, where the system determines the contact state with the virtual elastic object: **gripping with static contact, gripping with slipping contact, or released**. Corresponding **visual rendering** and **electrotactile stimulation signals** are then generated and delivered to both the **VR headset** and the **fingertip electrotactile interface** (updated every 5 ms).

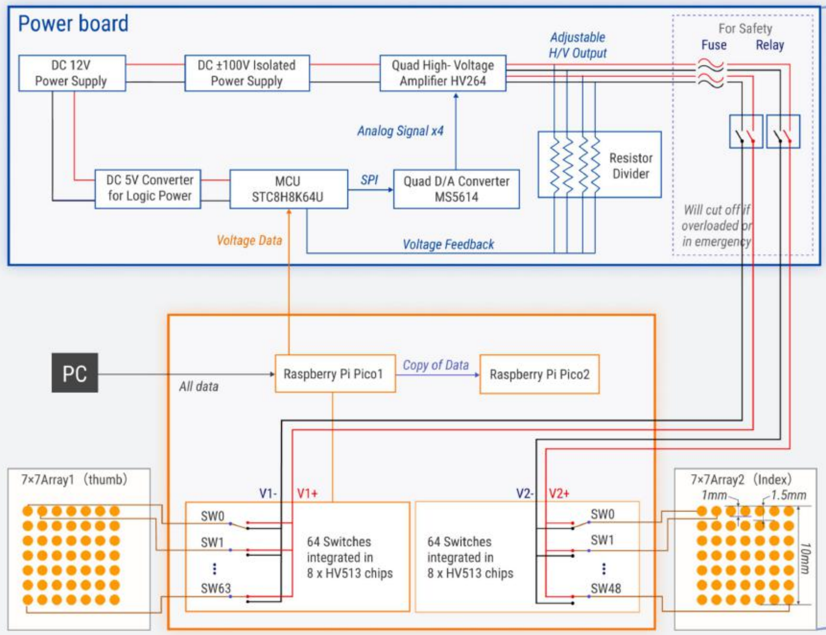
- Hand motion is tracked using a *Qualisys motion-capture system* with three *Arqus A5* cameras and *QTM 2021.2*.
- The state-determination and VR-rendering program was developed in *Unity 3D with C#*.
- Visual scenes are streamed to a *Meta Quest 2 headset via Oculus Link* over a wired connection.



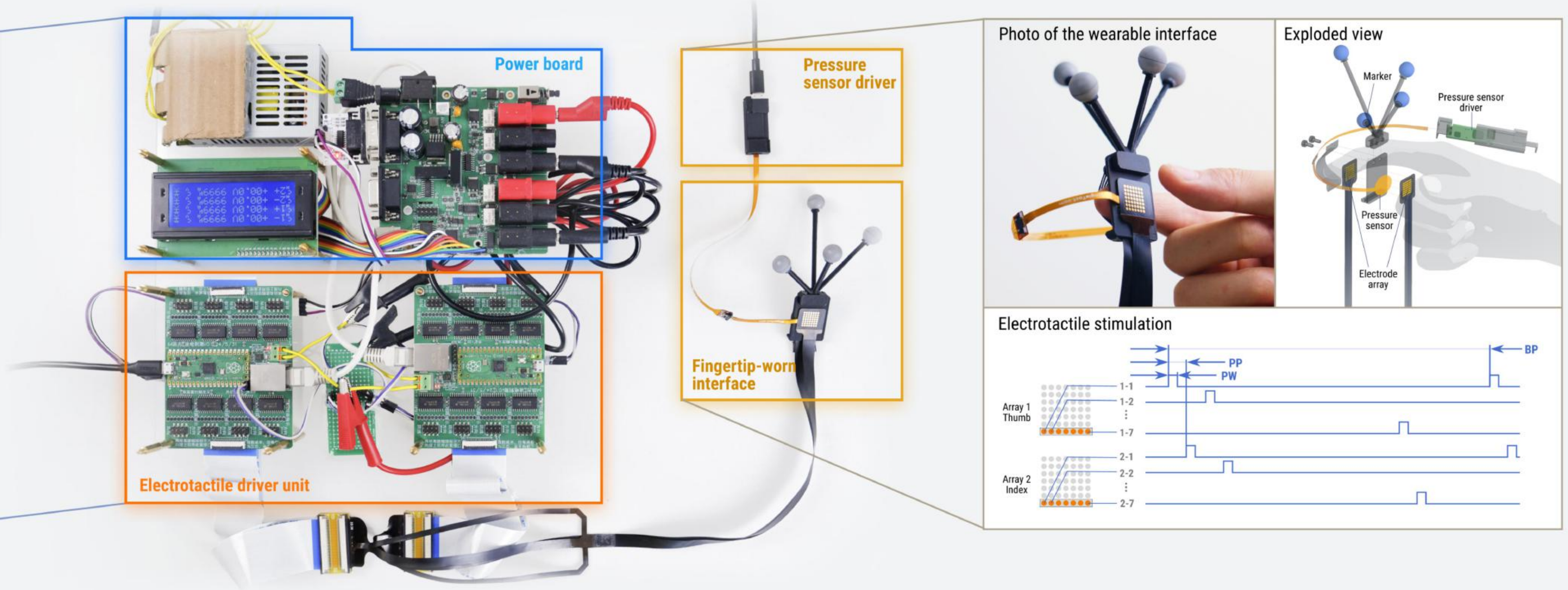




## ■ Key Hardware

**The electrotactile system includes a driver unit, power module, fingertip interface, and pressure sensor driver**. The *fingertip interface*, worn on the dominant index finger, integrates two 7×7 FPC electrode arrays (index and thumb sides) and a *thin-film SingleTact pressure sensor* beneath the thumb-side array. All components are mounted on a *rigid PLA frame* with retroreflective *motion-capture markers*, while the pressure-sensor driver sits on the back of the hand. Each electrode array is driven by a *high-voltage module* built with a Raspberry Pi Pico RP2040, Microchip HV513 chips, and a CH9120 Ethernet controller. The HV513 provides high-voltage outputs for independent electrode control (three states), and the 64-channel array updates within 1 µs. Communication runs via UDP over 10Base-T Ethernet. The system is powered by a 12 V DC supply, with converters generating low-voltage logic rails and a high-voltage HV264 amplifier (0–200 V). *Safety features* include current monitoring through a voltage divider and self-resetting fuses/relays that cut off high voltage during overload.




Schematic of E-Elasticity driver system



## ■ Key Algorithm

The system continuously monitors the user's lateral motion and normal force to determine the contact state, **static, slip, or release,** on every frame of the Unity program, providing corresponding visual and electrotactile feedback. **The distinction between static contact and slip depends on whether the actual grip force $F_{user}$ exceeds the expected force $F_{exp}$**; the calculation of the expected grip force required to prevent slipping ($F_{exp}$) is shown in ***Fig.E***. The release state occurs when there is no contact between the fingertip and the object, during which the cylinder returns to its natural state at a constant velocity.

❶ ***Visual rendering:*** If $F_{user} \geq F_{exp}$, the elastic cylinder is considered firmly gripped and fully deforms in response to the user's hand motion. The deformation between the fingertip and the fixed end is computed via linear interpolation. If $F_{user} < F_{exp}$, relative slip is detected: the object no longer follows the hand motion and instead returns toward its natural state at a constant velocity.

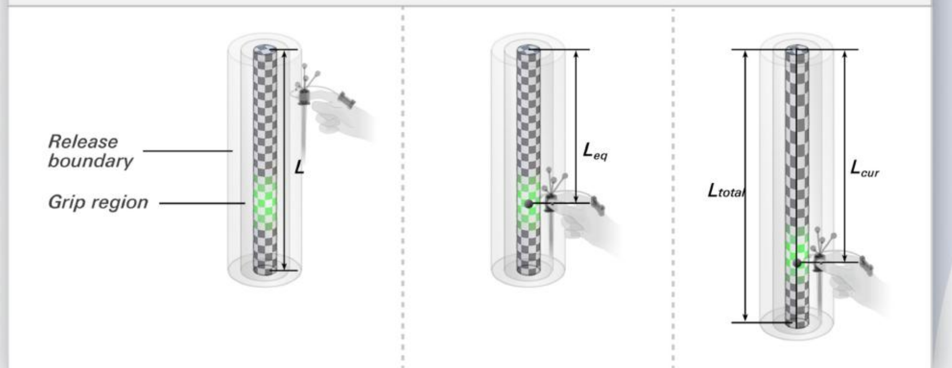
❷ ***Electrotactile stimulation for static friction:*** The static-friction sensation is rendered by activating a single line of electrodes (7 electrodes) on the 7×7 array (*Fig. F*). According to the real-world principle that stronger static friction produces greater lateral skin deformation, the perceived friction intensity and direction are determined by the position of this activated line, whose row index is computed as shown in Fig. F. Here, $D \in \{-1, 1\}$ denotes the direction of the line's movement, which is opposite to the direction of skin deformation. As $F_{exp}$ increases, the stimulation line gradually shifts toward the edge of the electrode array.

❸ ***Electrotactile stimulation for slip:*** Slip illusion is induced using a cyclical flowing-line pattern (*Fig.D*). An activation line moves across the electrode array at a constant velocity $V_{flow}$, aligned with the slip direction of the virtual object. When the line reached the boundary of the array, it reset to the starting position and continued looping, creating a continuous sensation of movement across the skin.

### Ⓑ Variable and constant definitions for contact state determination

| Type | Name | Unit | Description | Value |
|---|---|---|---|---|
| Constant | $k$ | N/m | Spring stiffness coefficient under natural (undeformed) conditions | 5 ≤ k ≤ 30, (μ=0.5) |
| | $\mu$ | N/A | Virtual static friction coefficient | 0.5 |
| | $R_{grip}$ | mm | Radius of the interaction zone for grip detection (The center of the circle is the central axis of the cylinder) | 30 |
| | $R_{release}$ | mm | Radius threshold for detecting release state | 45 |
| | $L$ | mm | Natural (resting) length of the virtual spring | 300 |
| | $V_{slip}$ | mm/s | Deformation rollback velocity under insufficient grip force | 10 |
| | $V_{release}$ | mm/s | Rebound velocity of the spring when fully released | 50 |
| | *deltaTime* | s | Time interval between two consecutive frames | 0.005 |
| | $F_{max}$ | N | Maximum allowable grip force for electrotactile rendering | 12 |
| | $V_{flow}$ | mm/s | The motion speed of the activated electrotactile line | 18 |
| Variable | $R_{finger}$ | mm | Minimum distance between the user's fingers and the spring's central axis | ≥ 0 |
| | $Pos_{finger}$ | N/A | World-space position of the user's fingertip avatar | N/A |
| | $deltaPos_{finger}$ | N/A | Frame-to-frame change in fingertip position (motion input) | N/A |
| | $F_{user}$ | N | Grip force applied by the user | ≥ 0 |
| | $k_{eq}$ | N/m | Effective local stiffness at the current grip position | ≈1.5*k |
| | $L_{cur}$ | mm | Distance from the grip point to the spring's fixed end | ≥ 0 |
| | $L_{eq}$ | mm | Resting length corresponding to the current grip point | ≥ 0 |
| | $L_{total}$ | mm | Current total length of the spring under deformation | ≥ 0 |
| | $F_{exp}$ | N | Expected grip force based on current deformation and stiffness | ≥ 0 |
| | $D$ | N/A | Indicate deformation direction (stretch vs. compress) | 0 or 1 |
| | *LineIndex* | N/A | Row or column index for selecting electrotactile stimulation line | 0, 1, 2, 3, 4, 5, or 6 |
| | *IsGrip* | N/A | Boolean flag indicating whether the system is currently in grip state | N/A |

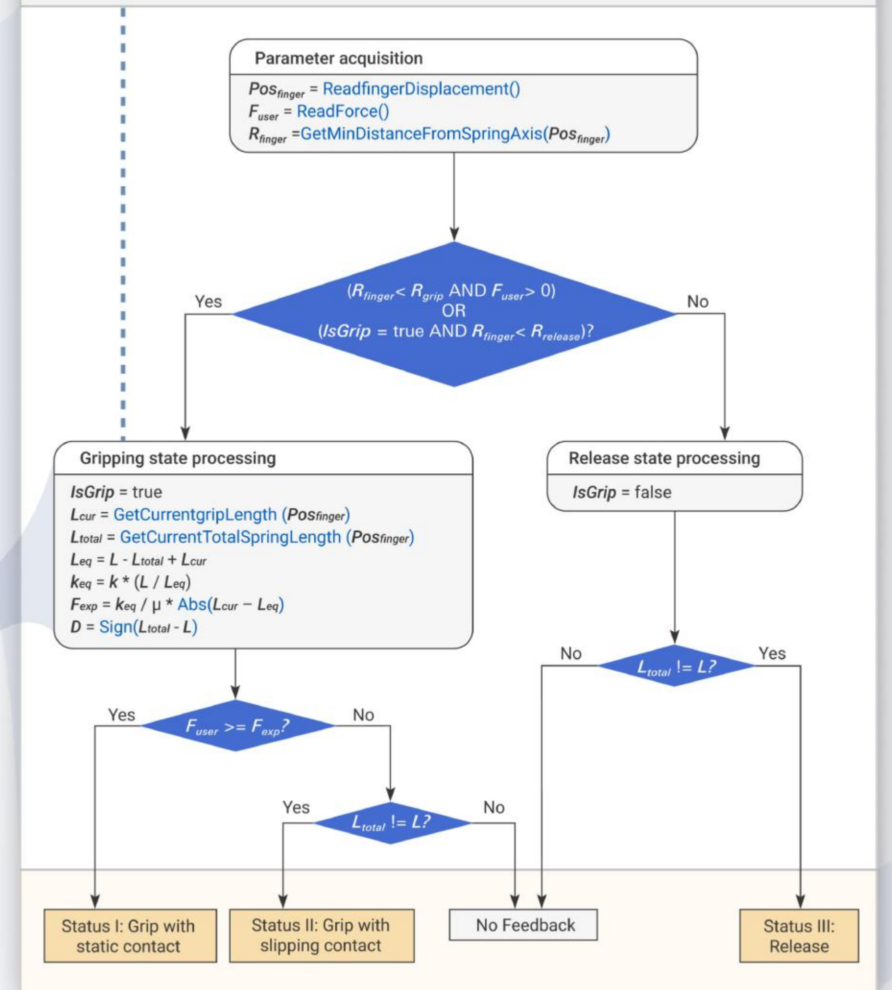
### Ⓒ Definition of length-related variables



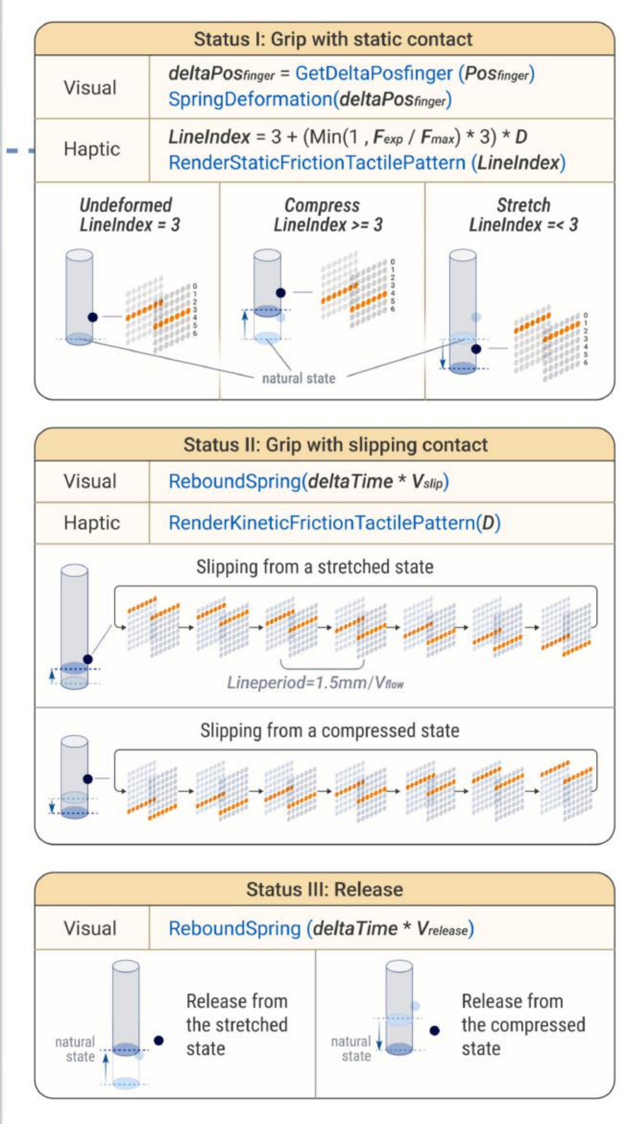

Ⓔ $$F_{exp} = \frac{k \cdot L_{total}}{\mu \cdot L_{eq}} \cdot (L_{cur} - L_{eq})$$

Ⓕ $$\text{lineIndex} = 3 + \left\lfloor \min\left(1, \frac{F_{exp}}{F_{max}}\right) \cdot 3 \right\rfloor \cdot D$$

### Ⓐ State decision flow (Every 5ms)




### Ⓓ Visual and haptic feedback for different state



## Experiments

**We conducted a series of experiments to systematically evaluate the perceptual effectiveness of the E-Elasticity system.**

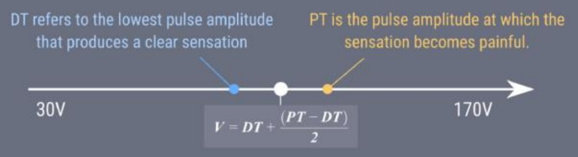
| Experiment No. | Purpose of the Experiment | Experimental Method | Core Data Analysis Method |
|---|---|---|---|
| Exp 1-1 | To verify whether electrotactile stimulation can induce illusions of static friction and slip. | 3×2 within-subjects design | Two-way repeated measures ANOVA |
| Exp 1-2 | | Three-way within-subjects design | Three-way repeated measures ANOVA |
| Exp 2 | To determine whether users can perceive directional elasticity rendered by E-Elasticity. | UWUD method measures JNDs, 7-point Likert-scale | Descriptive statistics |
| Exp 3 | To examine the relationship between perceived stiffness and virtual stiffness coefficient. | Within-subjects design | Linear regression analysis |
| Exp 4-1 | To test whether E-Elasticity generalizes beyond vertical compression/stretching tasks | Interview | NA |
| Exp 4-2 | To further evaluate the usability of E-Elasticity rendering the elasticity against that of conventional methods. | UWUD method measures JNDs, 7-point Likert-scale, interview | Repeated-measures ANOVAs |

**Participants**

Fifteen right-handed participants (6 females, 9 males), aged 21–29 (M = 23.13, SD = 2.06).

**Preparation**

Throughout the experiments, the stimulation voltage for both fingers was set to DT+0.5×(PT-DT).

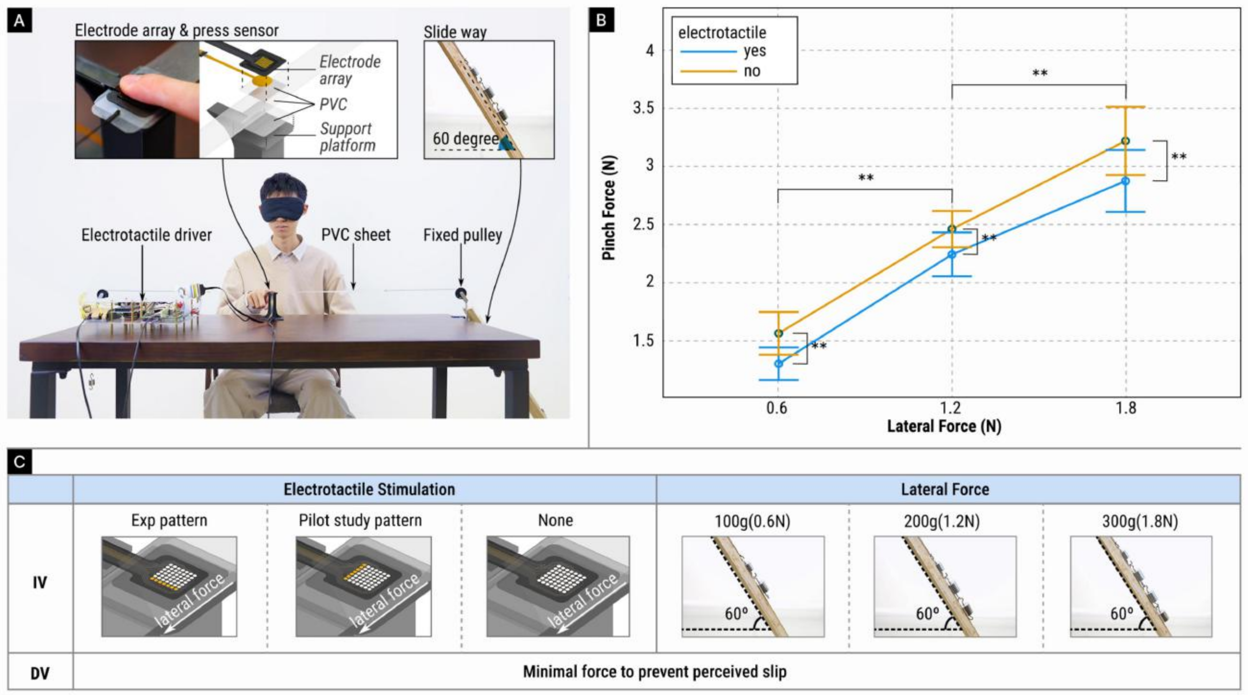



## Experiment 1-1: Static Friction Illusion

The experiment evaluated **whether electrotactile stimulation could induce a static-friction sensation**. Participants pressed their index finger onto a moving sheet (Fig. A), decreasing force when perceiving "static" contact and increasing it when detecting slip. A lower pressing force in the stimulation condition compared to the no-stimulation condition would indicate that the stimulation successfully induced a static-friction illusion, allowing participants to perceive the sheet as stationary even as slip tendency increased.

**Design:** A 3×2 within-subjects design with two variables (Fig.C): leftward traction force of the sheet (0.6 N, 1.2 N, 1.8 N) and electrotactile stimulation (present/absent).

**Result:** The stimulation reliably induced static-friction sensations across all conditions.

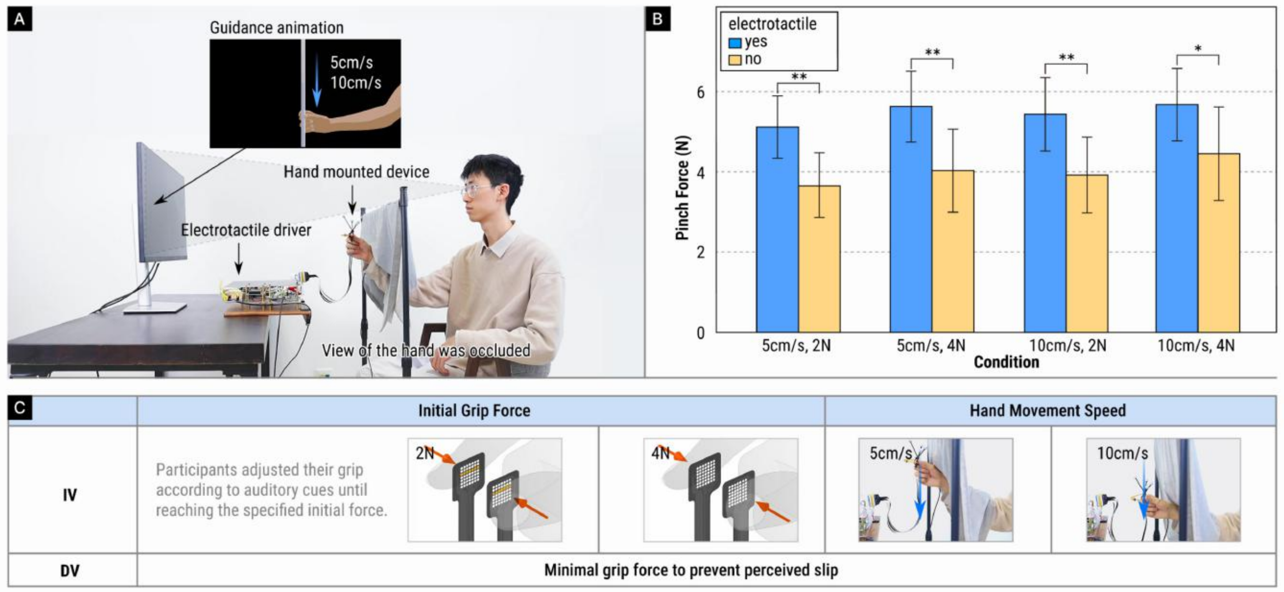



## Experiment 1-2: Slip Illusion

This experiment examined **whether electrotactile stimulation could induce a slip sensation**. With a device that continuously delivered a slip-pattern stimulus, participants attempted to grip a virtual suspended cylinder (Fig.A). They adjusted grip force until the cylinder felt securely held without slipping; this value was recorded as the minimum grip-force threshold. A higher threshold in the stimulation condition compared to the no-stimulation condition indicated that a slip illusion was successfully induced.

**Design:** A three-factor within-subjects design with electrotactile stimulation (present/absent), hand movement speed (5 cm/s vs. 10 cm/s), and initial grip force (2 N vs. 4 N).

**Result:** as shown in Fig. B, both stimulation and movement speed produced significant main effects on grip force; The stimulation reliably induced slip illusion across all conditions.

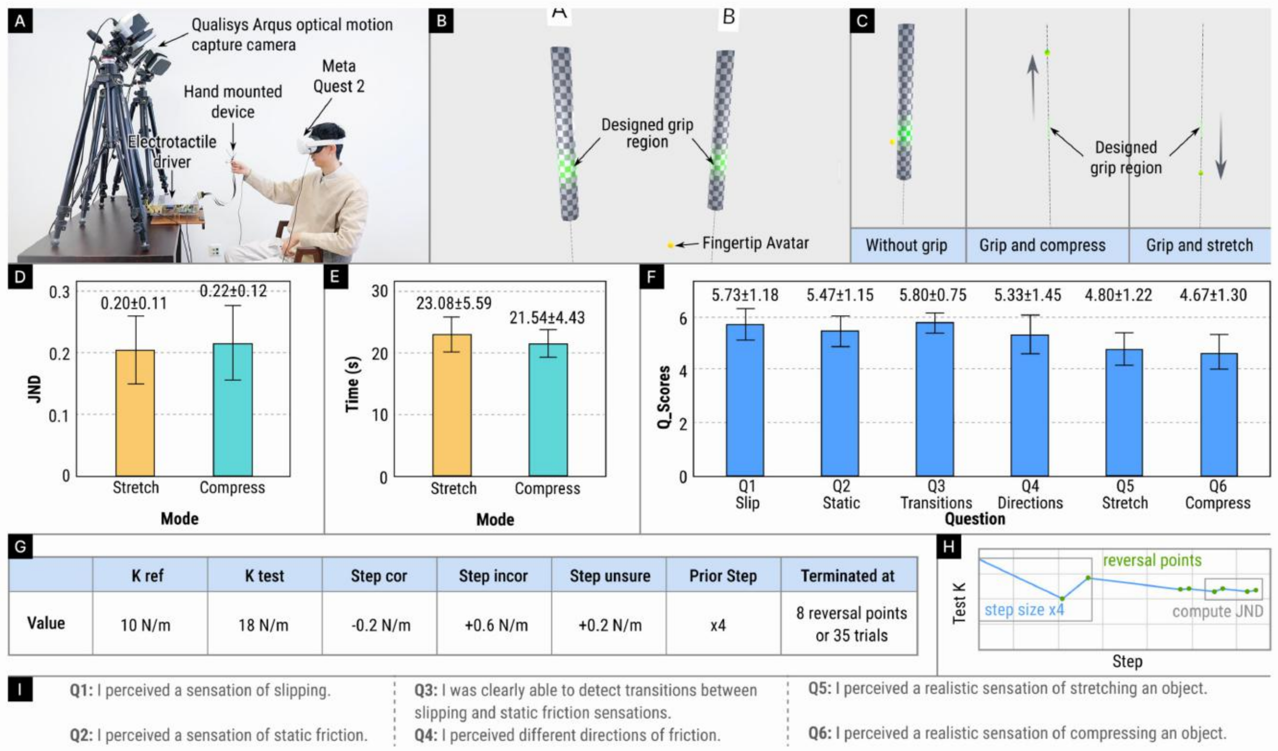



## Experiment 2: Virtual Stiffness Discrimination

This experiment **assessed E-Elasticity's capability to render elasticity through static and dynamic friction cues**. It measured the system's stiffness-discrimination performance using the just noticeable difference (JND) and evaluated participants' perceptual experience. In each trial, participants judged which of two virtual cylinders felt stiffer or indicated uncertainty (Fig. A, B). Once the cylinder was initially gripped, its visual mesh disappeared, leaving only its central axis visible (Fig. C).

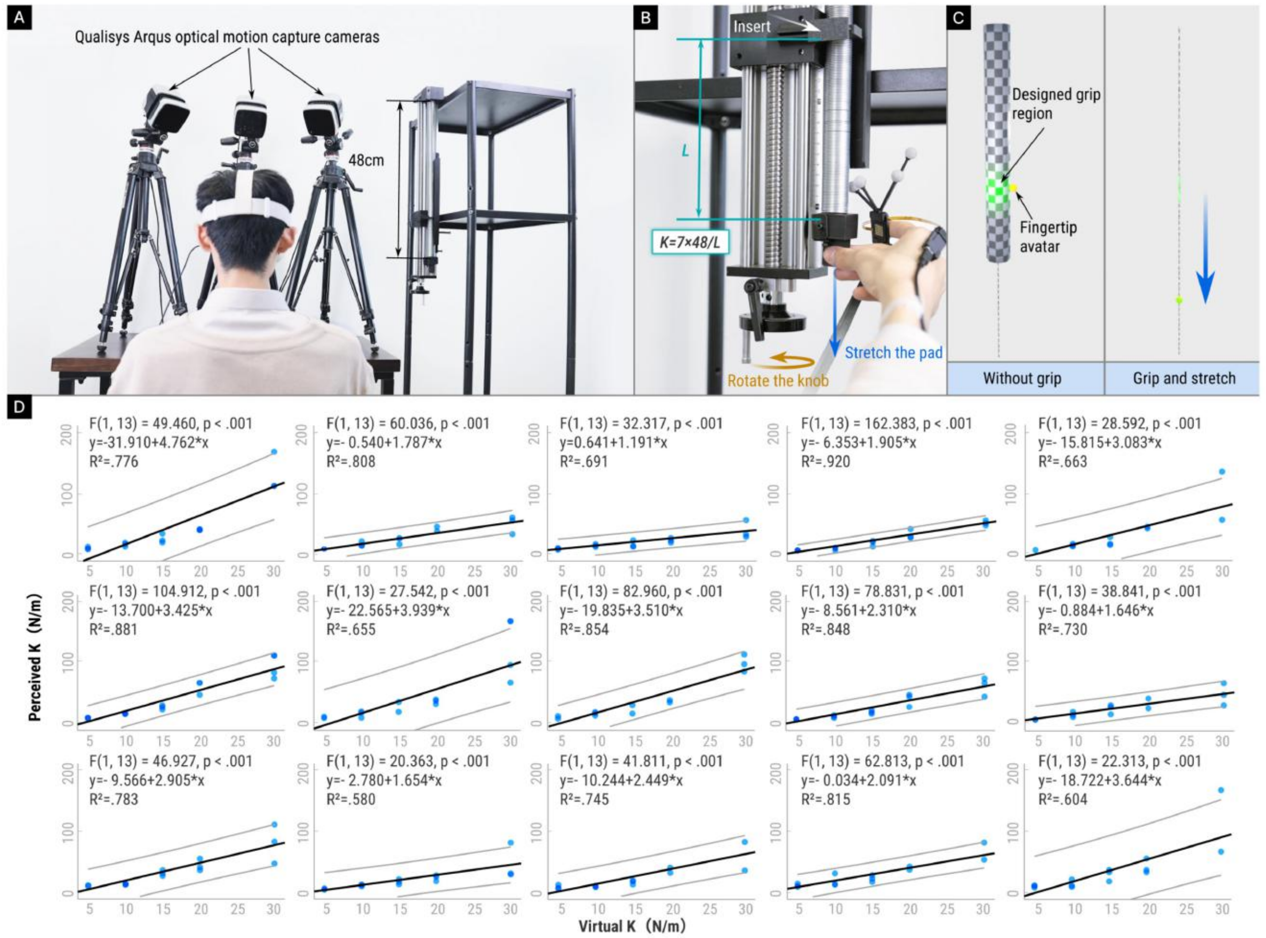
**Design:** Virtual-stiffness JNDs (stretching/compressing) were measured using the Unforced Weighted Up-Down (UWUD) method (parameters in Fig. G), followed by a Likert-scale rating of perceptual experience.

**Result:** As shown in Fig. D, the JND was approximately 0.2, demonstrating strong elasticity-rendering performance.



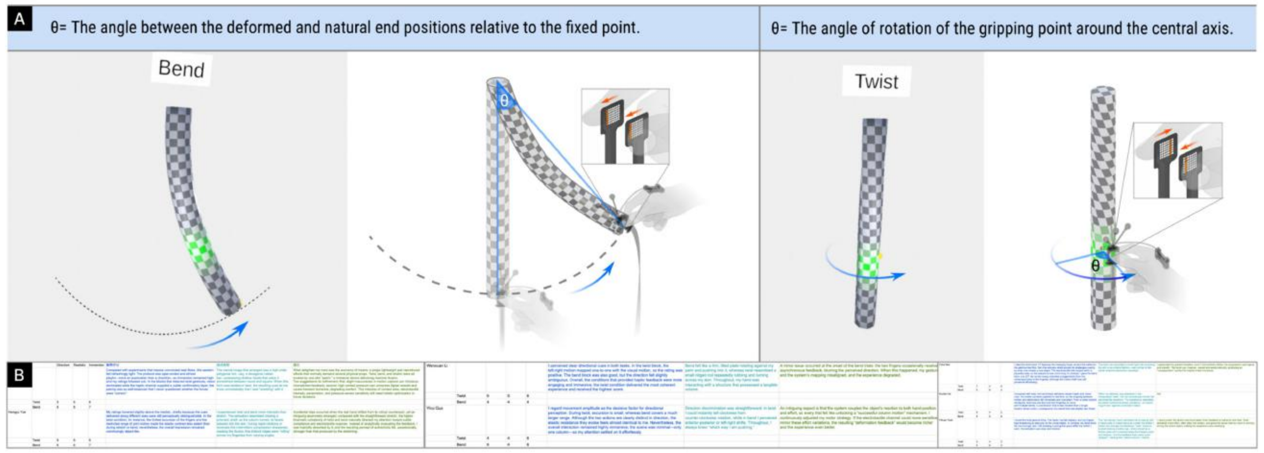
## ■ Experiment 3: Mapping Virtual Stiffness to Perceived Stiffness

This experiment examined **how virtual stiffness values correspond to perceived stiffness in physical units.**
Design: Five virtual stiffness levels (K = 5, 10, 15, 20, 30 N/m) were tested. After experiencing each virtual stiffness level, participants adjusted the stiffness of a spring-based physical device to match what they felt in VR (Fig. A–C), and the resulting physical stiffness value was recorded as the perceived stiffness.
**Result:** Linear regression analysis (Fig. D) showed a consistent trend across participants: higher virtual stiffness values yielded correspondingly higher perceived stiffness in physical units.



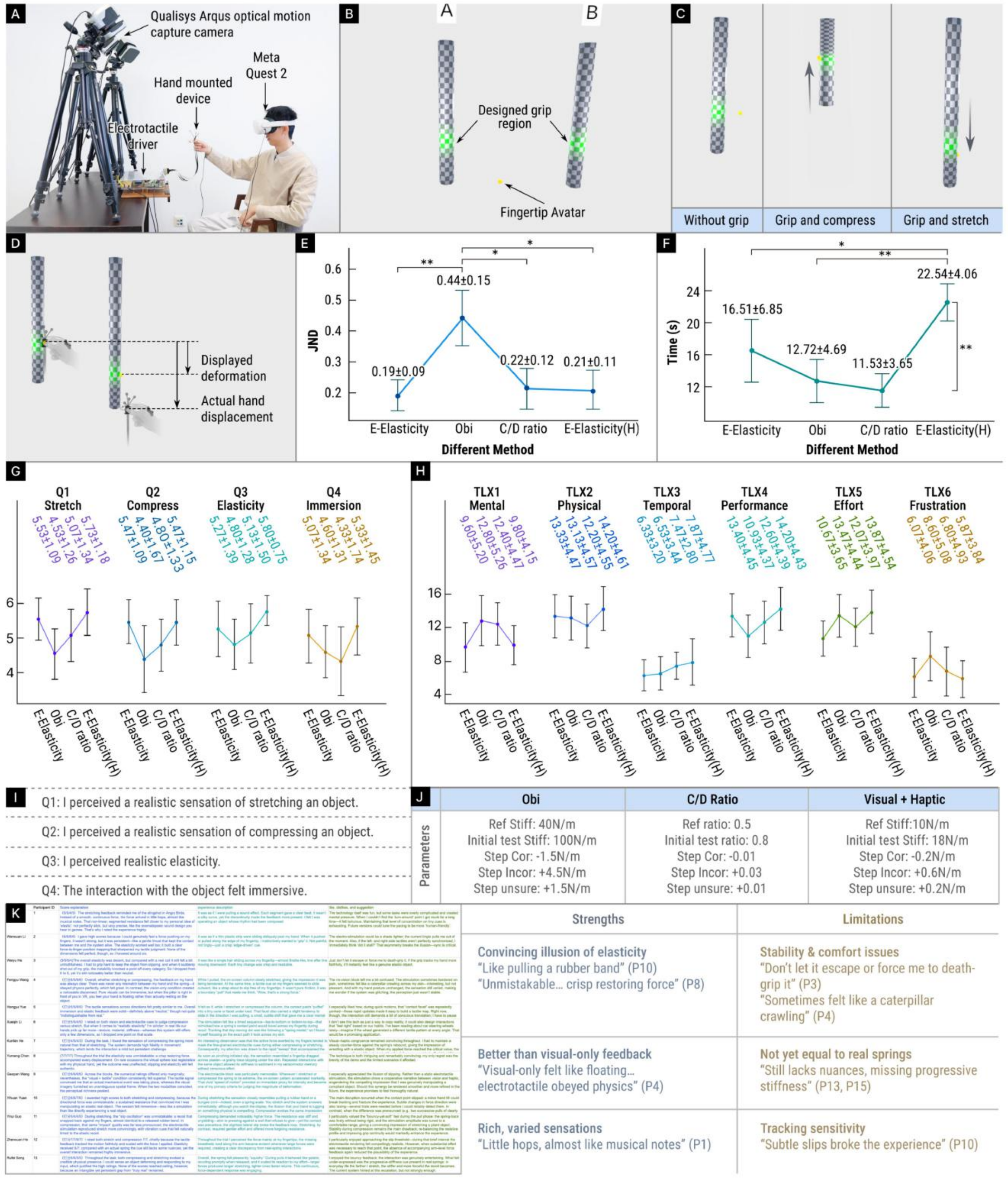

## ■ Experiment 4-1: Bend & Twist

To test **whether E-Elasticity can generalize beyond vertical compression/stretching**, we introduced two interaction modes: Twist, where deformation occurs through rotation about the cylinder's central axis, and Bend, where deformation arises from horizontal bending. In both modes, $F_{exp}$ was computed following θ (Fig. A).
**Result:** All seven participants rated the realism and immersion of both modes highly during post-experiment interviews (Fig. B).

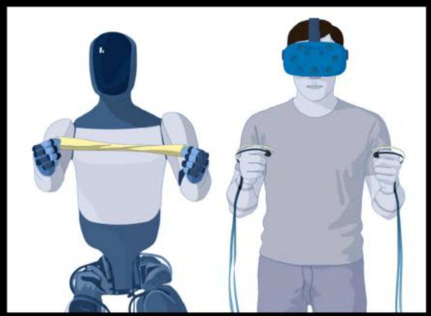



## ■ Experiment 4-2: Comparing Stiffness Simulation Methods

We **evaluated E-Elasticity (with/without visual feedback) against two established elasticity-simulation methods: the Obi method and the C/D ratio method.** The comparison focused on stretch-stiffness JNDs and perceptual experience (using the same measurement procedures as Experiment 2). The Obi method is purely visual, rendering elasticity via a spring–mass physics model; the C/D-ratio method is pseudo-haptic, altering perceived stiffness by adjusting the ratio of hand displacement to object deformation (Fig. D). The experimental setup is shown in Fig. A and B, and the cylinder's visual rendering (visual-feedback condition) in Fig. C.
**Result:** The Obi method produced higher JNDs; E-Elasticity (haptic-only) resulted in longer completion times. Interviews (Fig. K) revealed that participants experienced vivid elasticity through electrotactile feedback, often describing it through metaphors. Many explicitly contrasted it with visual-only or other non-haptic methods, valuing its immersion, novelty, and convincing illusion of elasticity, while also identifying areas for refinement.



## Applications



### Robotic Teleoperation

Haptic feedback in teleoperation control loops can enhance coordination, and complex task performance. During stretching, twisting, or bending with the gripper, electrotactile stimulation on fingers provides corresponding haptic feedback of variable resistance. We demonstrated this in tasks like:

- B Twisting wet cloth
- C Stretching tissue
- D Bending USB cable

### Surgical Training

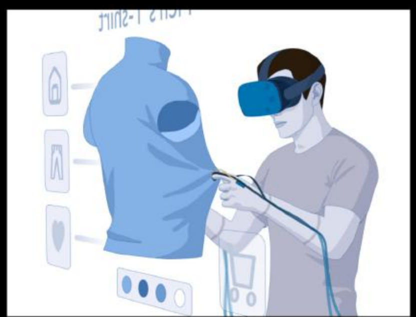
Haptic feedback conveys key tissue properties, such as hardness and position. Most surgical training systems lack these cues, hindering surgeons' accurate perception and response. E-Elasticity addresses this by rendering force and stiffness through electrotactile feedback:

- E *Thyrocricocentesis surgery*
- F *Cardiovascular interventions*

### Education

Force and kinesthetic feedback enhance learners' reasoning and conceptual understanding. With its rich force and tactile cues, the E-Elasticity system can support tasks such as:

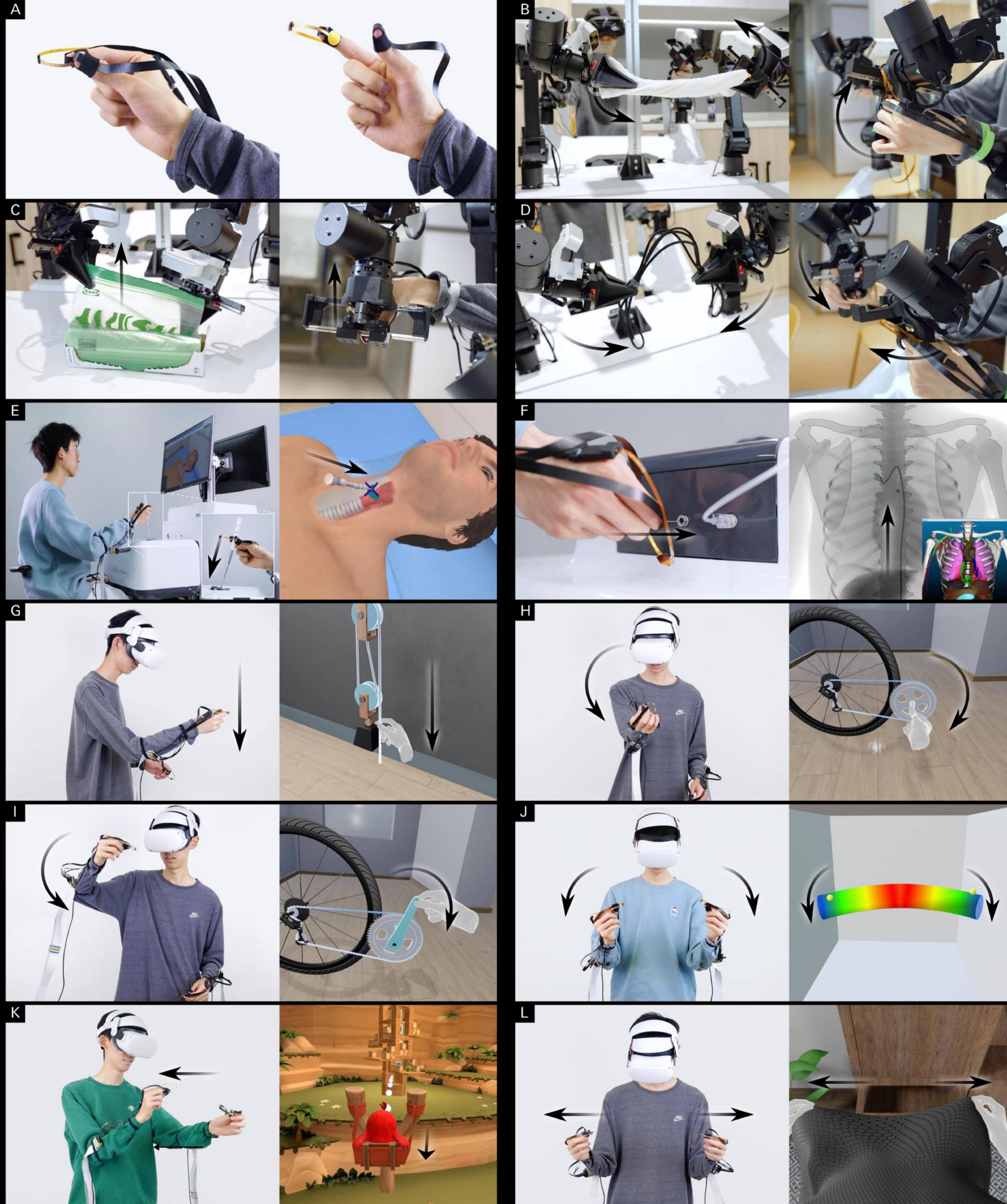
- G *Perceiving pulleys*
- H I *Perceiving gears*
- J *Perceiving elastic materials*



### VR Gaming and Life

E-Elasticity enables realistic haptic perception in VR gaming and everyday VR interactions, enhancing the accuracy of material perception:

- K Helps users control slingshots precisely
- L Simulates fabric elasticity in VR fashion



## Research Paper

**Contribution**

***Fourth Author***

Prototype Development; User Study Execution;
Application Scenario Development

**Collaborator**

Hongnan Lin, Lei Gao, Shengsheng Jiang, Ziyi Fu, et al.

**Keywords**

Electrotactile Technology, VR, Weight Perception

**Instructor**

Prof. Teng Han, Director of HCI lab, Institute of Software, Chinese Academy of Sciences

**Status**

Published at ***CHI 2025***

02

# Slip-Grip

## An Electrotactile Method to Simulate Weight

Weight perception is a fundamental part of interacting with real-world objects, and incorporating it into VR can significantly enhance immersion: imagine truly feeling the heaviness of an apple or a glass of water in a virtual scene. However, delivering weight sensations in a lightweight form factor remains a persistent challenge.

We introduce an electrotactile weight simulation method that enhances weight perception by inducing a slip illusion. When the user applies insufficient force, the system delivers a specific electrotactile pattern to create a slipping sensation, prompting the user to subconsciously tighten their grip and thereby perceive the virtual object as heavier. Multiple user studies have shown that this method reliably elicits the slip illusion and substantially enhances perceived weight in VR.

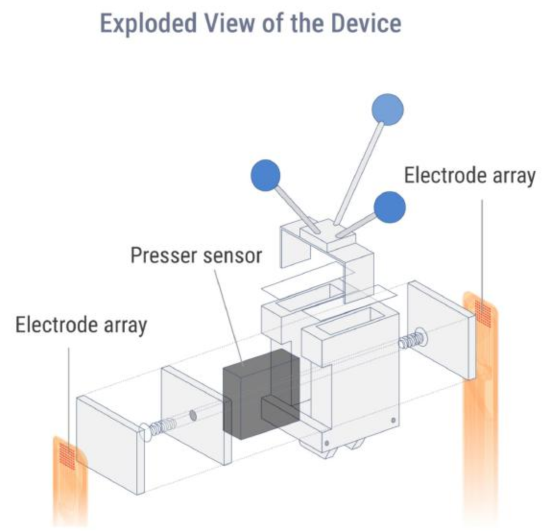
*https://youtu.be/KZZNlEhBynE*

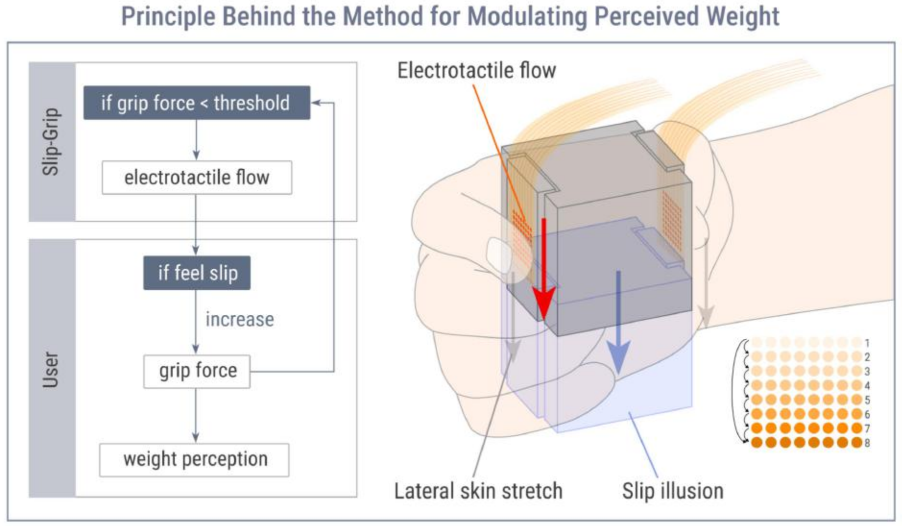
*July 2024 – September 2024*

*Human–Computer Interaction Technology and Intelligent Information Processing Laboratory, ISCAS, Beijing, China*

### Methods

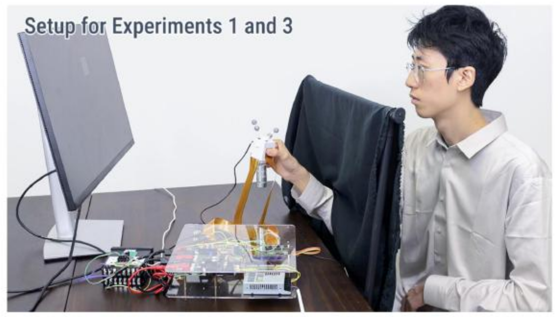
Slip-Grip is based on the finding that the **perceived weight of an object** is influenced by the **grip force applied** when lifting it. We designed a prototype consisting of two 8×8 electrotactile arrays and a pressure sensor. When the user's grip is too weak, the device delivers a **downward electrotactile stimulation flow to induce a slip illusion,** prompting the user to instinctively **tighten their grip** to prevent the object from slipping. Once the grip force reaches the predefined threshold, the stimulation stops, allowing the user to form a stable perception of weight.



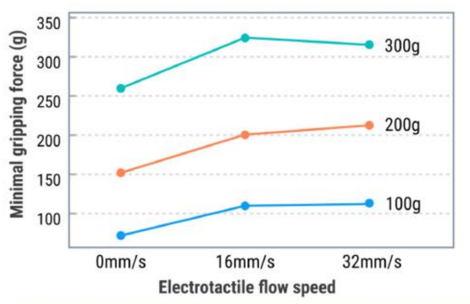



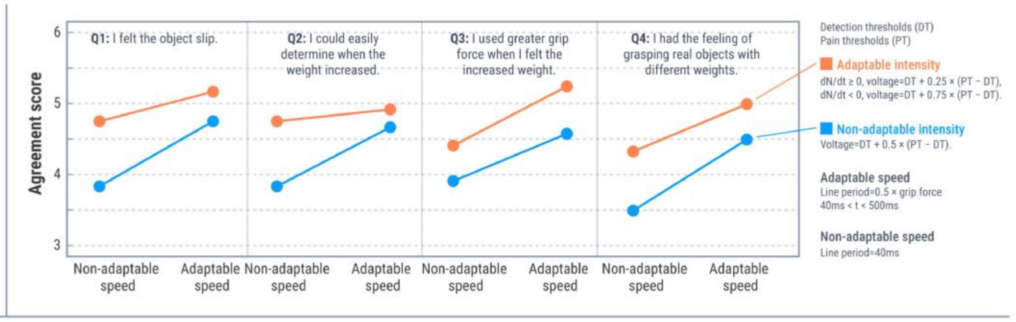

### Experiments

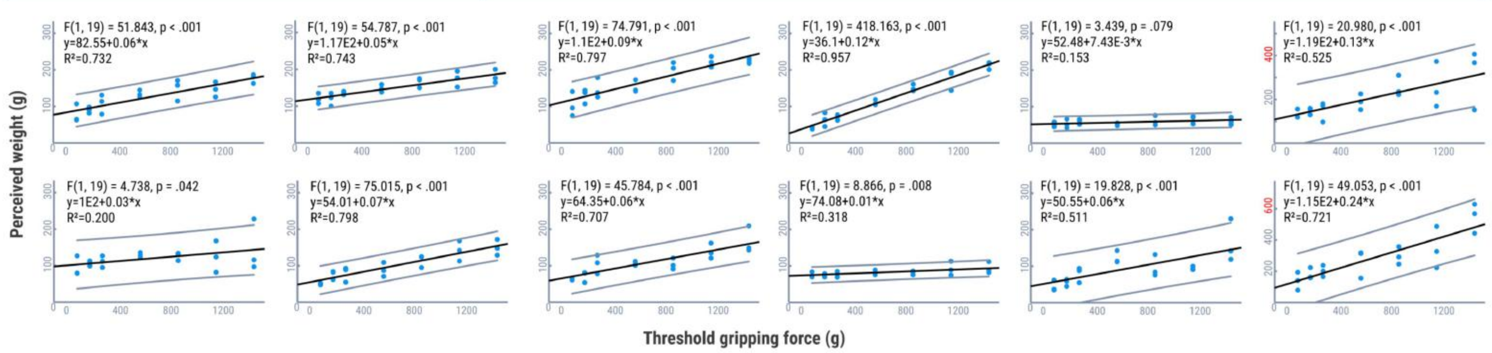
We conducted a series of user studies to validate this approach. **Experiment 1** examined whether electrotactile stimulation patterns could successfully induce a slip illusion during a weight-gripping task. **Experiment 2** explored different strategies for enhancing perceived weight in VR. **Experiment 3** investigated the relationship between grip force and perceived weight. The results show that by modulating grip force via electrotactile feedback, **our system can effectively simulate a range of virtual weights.**







## Application 1: Teleoperation

*eg. Perceiving the weight of an object held by a robotic arm's gripper*

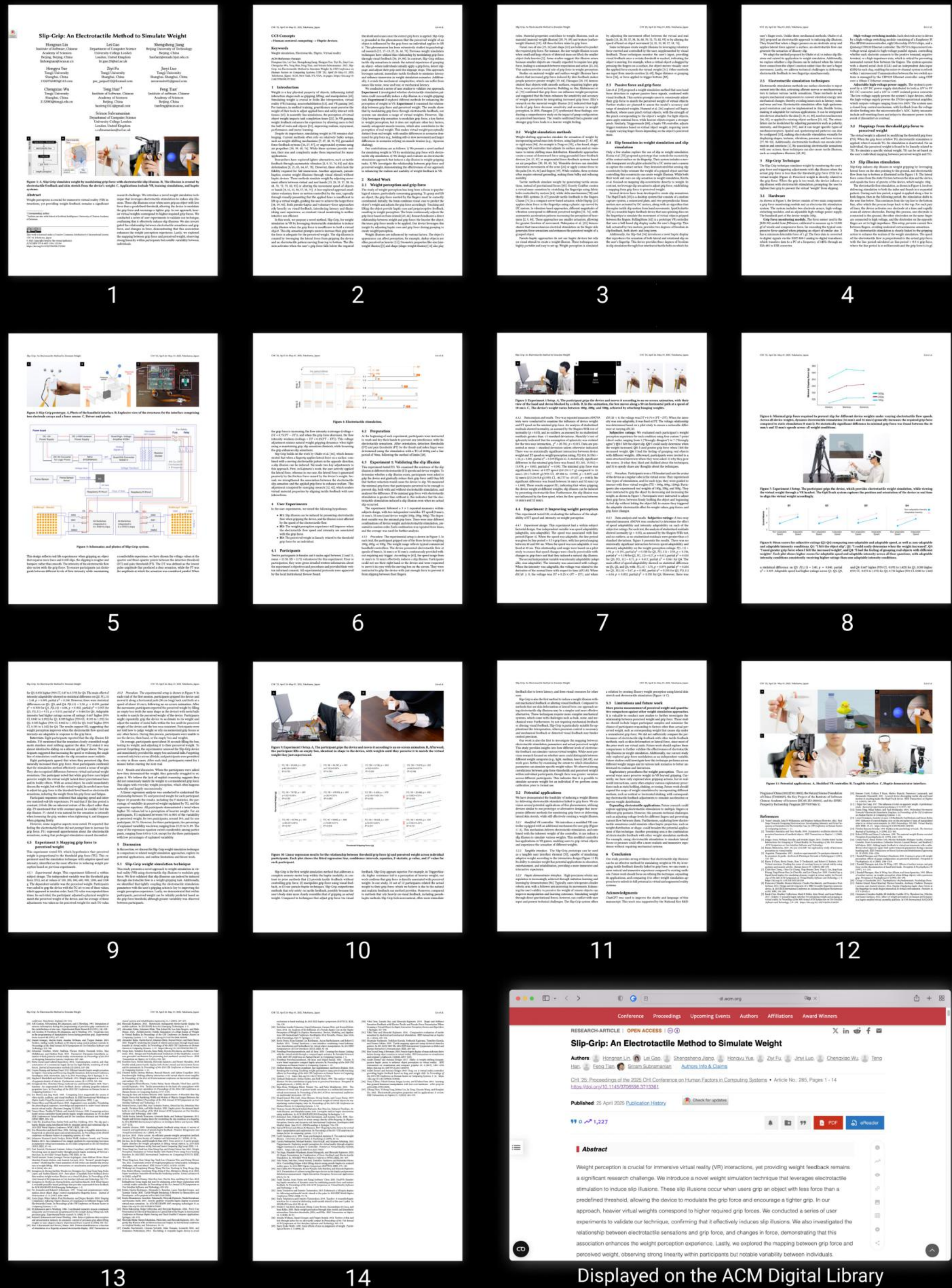
## Application 2: VR Gaming

*eg. A controller that conveys virtual object size and weight*

## Application 3: Education

*eg. Experiencing how the same object feels under different planetary gravities*

The paper was ultimately published at CHI 2025. The full content is available at:
https://doi.org/10.1145/3706598.3713361



## Two-Person Collaborative Project

**Contribution**
***First Inventor on the Patent***
Concept Development; Circuit Structure Design; Product Design

**Keywords**
Wearable Device, Electrotactile Technology, Integrated Product Design

**Collaborator**
Ruiyi Liu

**Achievements**
Gold Award, Design Intelligence Award(2025)
Silver Winner, MUSE Design Awards (2025)
Finalist, Better Design Award (2025)

**Status**
Invention Patent (Filed)

DESIGN INTELLIGENCE AWARD

03

# EXILO

## The Next-Generation Haptic Glove

Through research practice, I recognized that haptic feedback is essential for immersive VR, yet most existing devices remain heavy, costly, and difficult to deploy beyond laboratory settings.

To address this, we developed EXILO, a high-resolution electrotactile glove. At present, **it is the lightest, most precise, and most cost-effective wearable haptic device on the market.** Meanwhile, its micro-elastic structures allow it to closely conform to hand contours, ensuring comfort during wear.

EXILO has the potential to make high-quality haptics more accessible in everyday VR applications. This invention also **served as the technological foundation for the founding of my company, Frontier.**

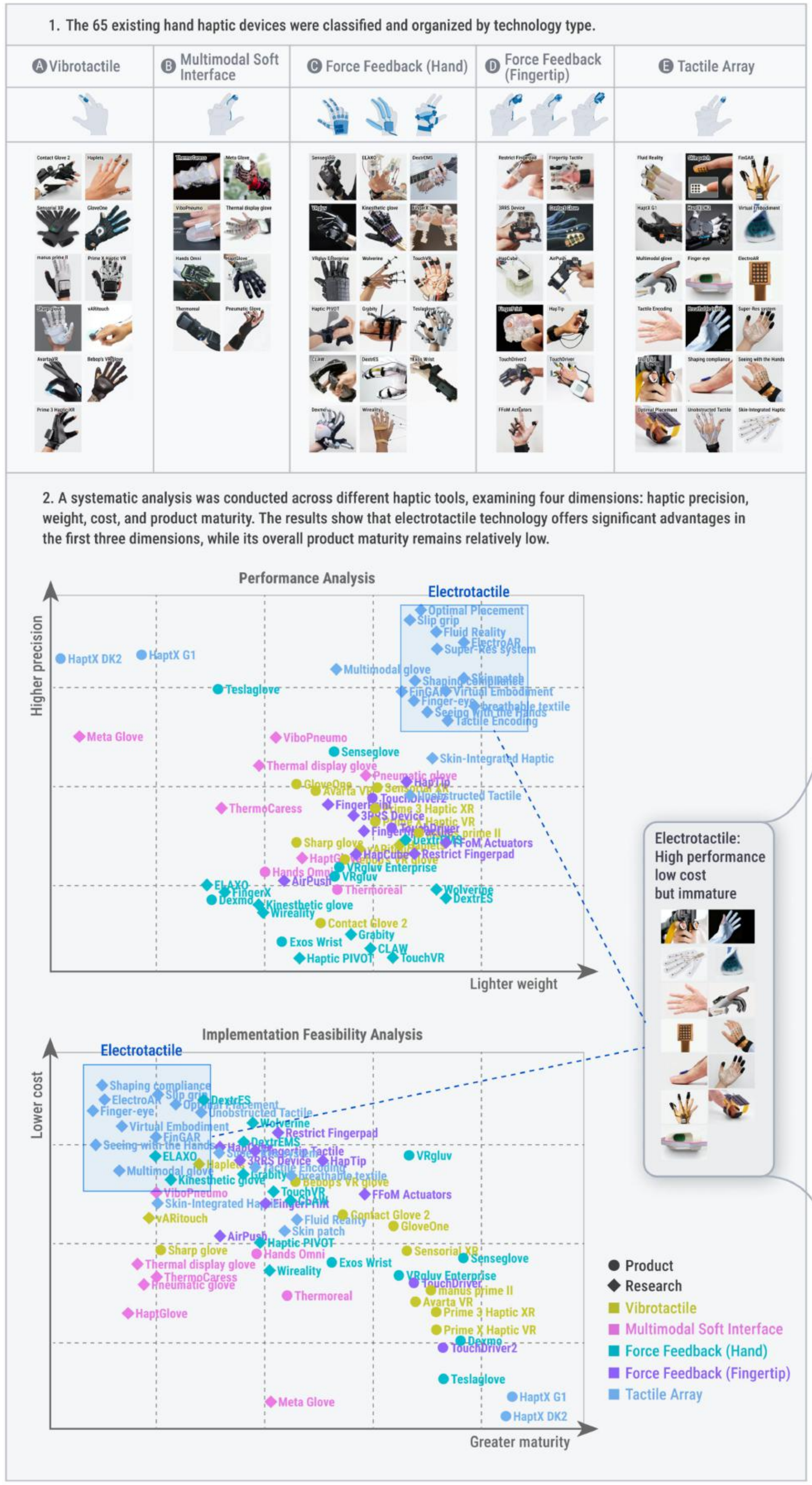
[https://youtu.be/vs7dGUYnmm8](https://youtu.be/vs7dGUYnmm8)

*December 2024 – May 2025*
*Human–Computer Interaction Technology and Intelligent Information Processing Laboratory, ISCAS, Beijing, China*

## EXILO's Ideation and Development Framework

Most current VR experiences lack haptic feedback, which not only distorts immersion but also creates major challenges for precise interaction. Although haptic technology continues to advance, performance constraints and bulky hardware still hinder its adoption. After classifying 65 existing hand haptic devices, I found that **electrotactile technology offers clear advantages in haptic precision, weight, and cost** compared with traditional approaches. However, there is no mature commercial electrotactile product available, leaving a noticeable market gap. Based on prior research and hands-on experience, I identified four core challenges preventing electrotactile technologies from reaching product-level maturity. To address these challenges, I designed six key solutions, which ultimately led to the development of the next-generation electrotactile glove, EXILO.

### I. Research and Analysis of Existing Hand Haptic Devices → II. Productization Challenges of Electrotactile Technology → III. Possible Solutions →




**Skin-Integrated Haptic** — Ya Huang et al., 2023, Nature Electronics

**Tactile Encoding** — Kuanming Yao et al., 2022, Nature Machine Intelligence

**ElectroAR** — Jonathan Tirado et al., 2020, EuroHaptics 2020

**Shaping Compliance** — Arata Jingu et al., 2024, CHI 2024

**FinGAR** — Vibol Yem et al., 2016, SIGGRAPH 2016

**Finger-eye** — Zhiming Liu et al., 2016, IEEE RCAR

**Virtual Embodiment** — Martin A Garenfeld et al., 2024, IEEE Transactions on Haptics

**Multimodal Glove** — Colin V. Keef et al., 2020, Advanced Intelligent Systems

**Seeing with the Hands** — Shan-Yuan Teng et al., 2025, CHI 2025

**Super-Res System** — Weikang Lin et al., 2022, Science Advance

**Optimal Placement** — Michiru Sobue et al., 2025, CHI 2025

**Slip-Grip** — Hongnan Lin et al., 2025, CHI 2025

**Breathable Textile** — Kuanming Yao et al., 2024, Science Advance

### Challenges

Challenge I. The stiffness of the Flexible Printed Circuit (FPC) prevents the stimulation electrodes from conforming tightly to the curved surface of the hand.

Challenge II. Sweat can easily oxidize the electrodes, resulting in performance degradation after long-term use.

Challenge III. Existing glove-based wearable devices often interfere with hand-motion tracking systems.

Challenge IV. The driver module is too large and heavy, making full wearability difficult to achieve.

### Possible Solutions

**Solution I.** Introduce a micro-serpentine structure into the FPC substrate around the electrodes to increase elasticity at low cost, allowing it to conform to complex hand curvatures.

**Solution II.** Design an integrated self-locking structure at the fingertips to enable adjustable tightness.

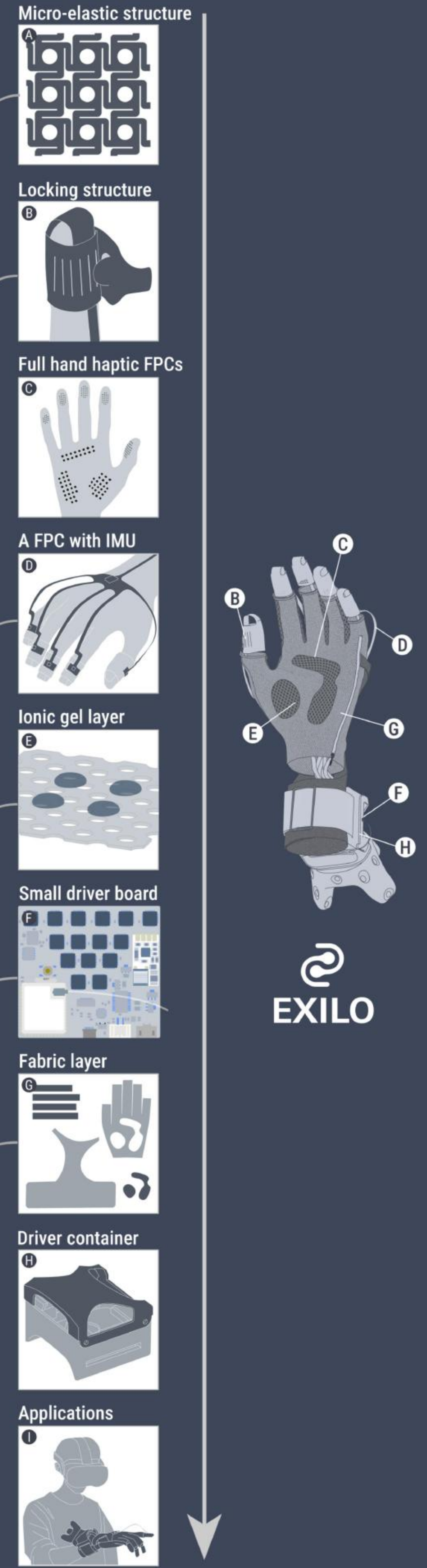
**Solution III.** Integrate IMU modules into the fingertip FPCs and add support for attaching an HTC VIVE tracker to improve compatibility with hand-motion tracking.

**Solution IV.** Add an ionic-gel layer to the palm area to improve adhesion and enhance tactile sensation.

**Solution V.** Reduce the volume and weight of the driver module to improve overall wearability.

**Solution VI.** Design an outer fabric structure that allows easy replacement of FPC components, improves breathability, and provides sufficient structural support.

## Development

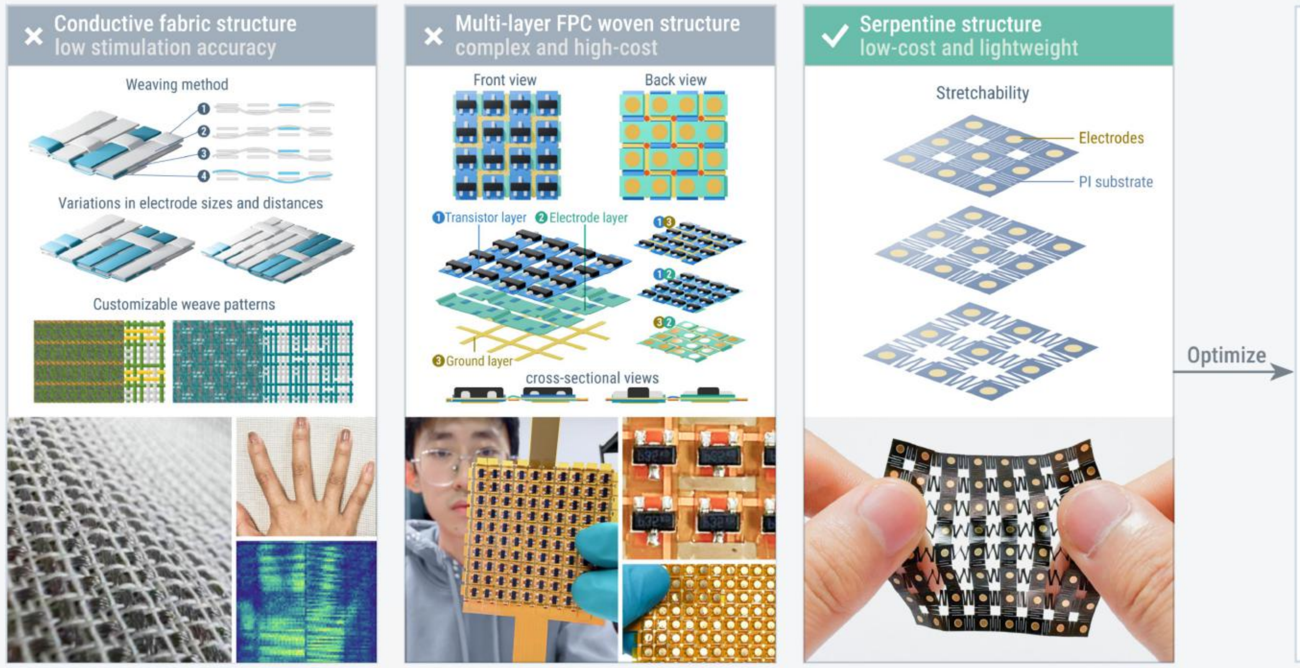


## Enhancing FPC Elasticity through Micro-Serpentine Structure

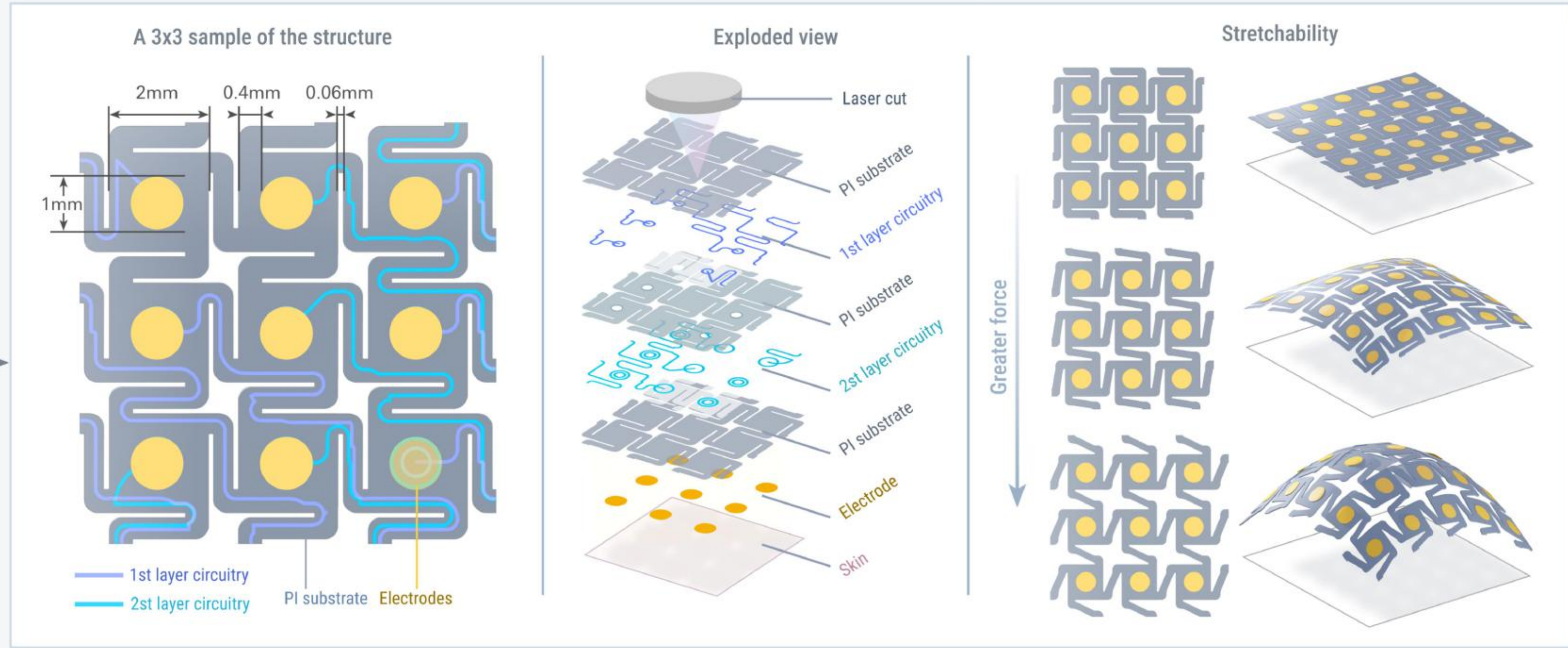
The Flexible Printed Circuit (FPC) substrate that carries the stimulation electrodes is typically both tough and rigid. The mismatch between the FPC and the curvature of the human hand makes it **difficult for the electrodes to maintain stable skin contact**, which compromises the haptic experience. Therefore, the electrotactile interface required a redesign. I tested multiple FPC structures, but most of them have limited practical viability.

Ultimately, I selected a **lightweight, low-cost, and highly malleable single-layer serpentine structure**. By engraving micro-serpentine elastic patterns into the Polyimide (PI) substrate between electrode arrays, the substrate gains elasticity, **allowing the electrodes to conform to complex curved surfaces without breaking or warping**. This micro-serpentine structure is applied to all subsequent haptic FPC designs.

### Testing of Different Structures

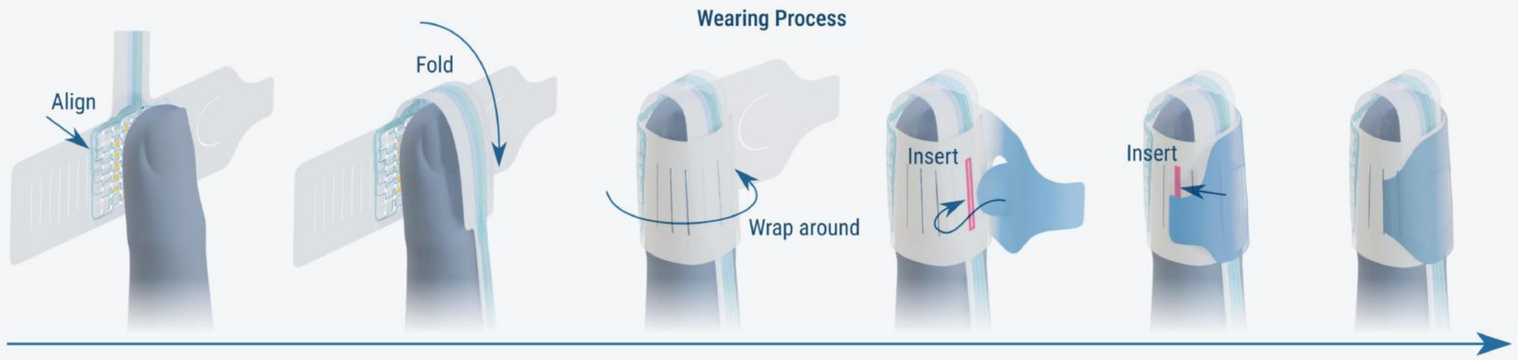


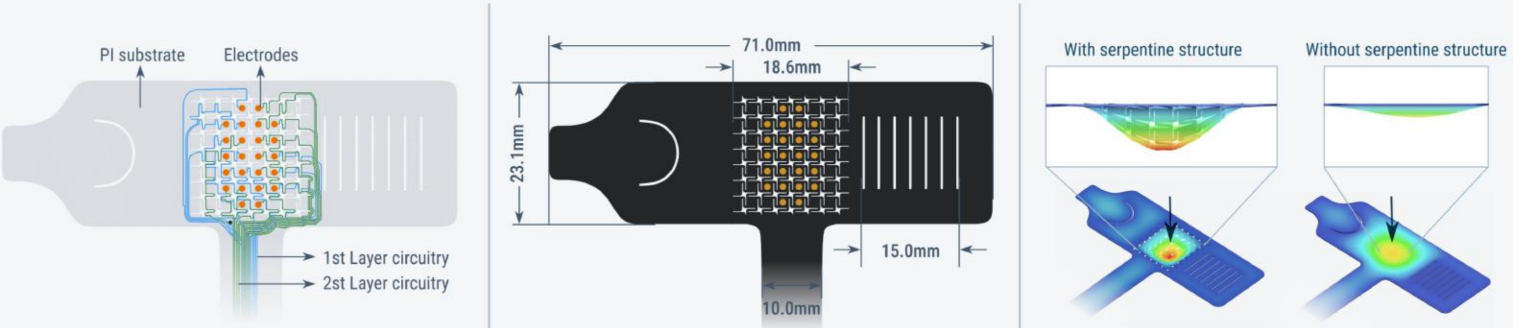

### Micro-Serpentine Structure Design




## Adjustable Fingertip-Locking Structure

At the fingertips, the **elastic electrode arrays need to be tightened to conform to the finger pads**, yet finger thickness varies widely. To address this, an adjustable locking structure was required. We designed a **self-locking structure using the substrate surrounding the electrode array** and completed the internal circuit layout accordingly. This structure enables convenient, lightweight multi-level tightness adjustment and can be manufactured simply by laser-cutting it together with the serpentine structure.

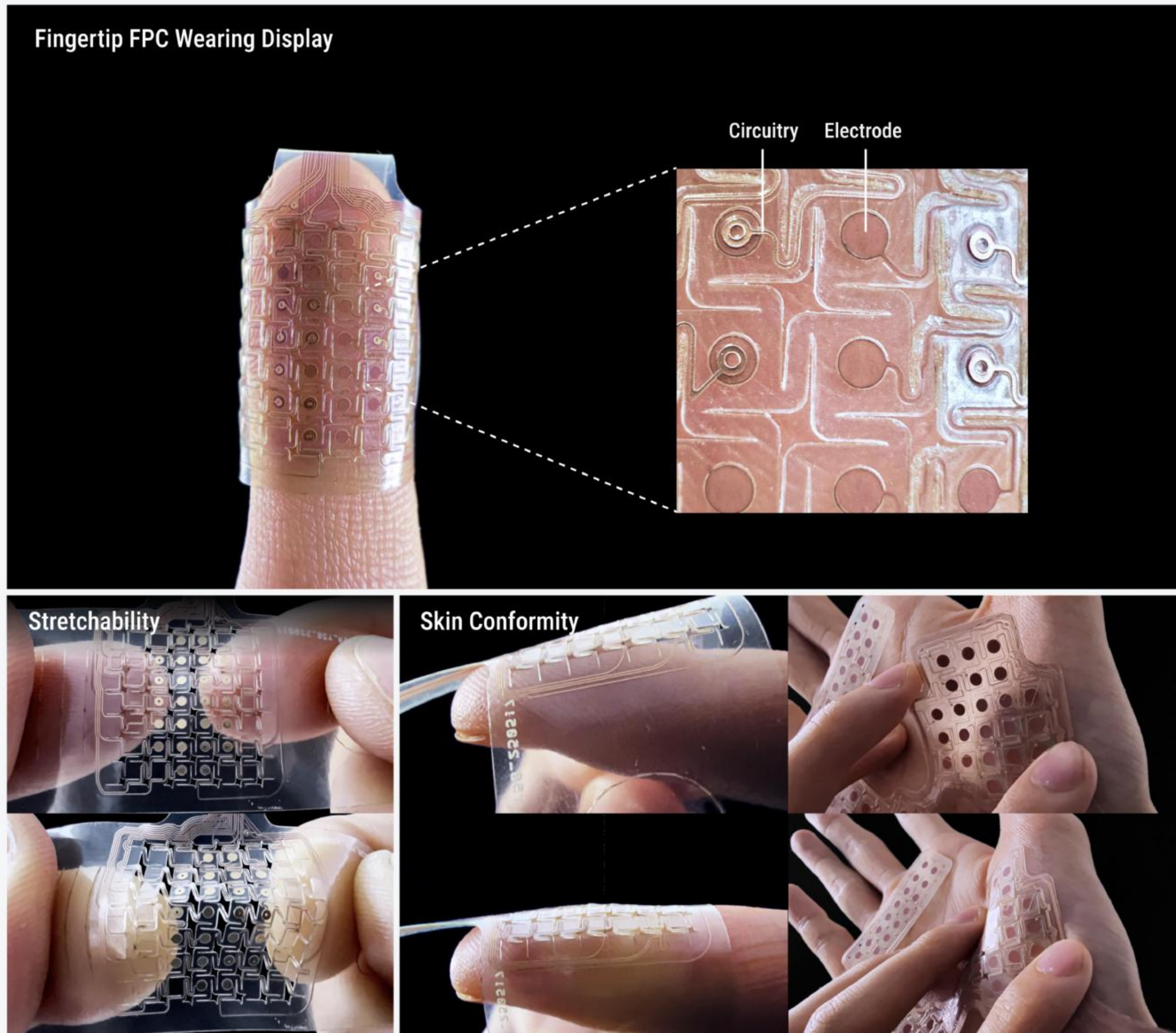



Circuit layout of fingertip FPC

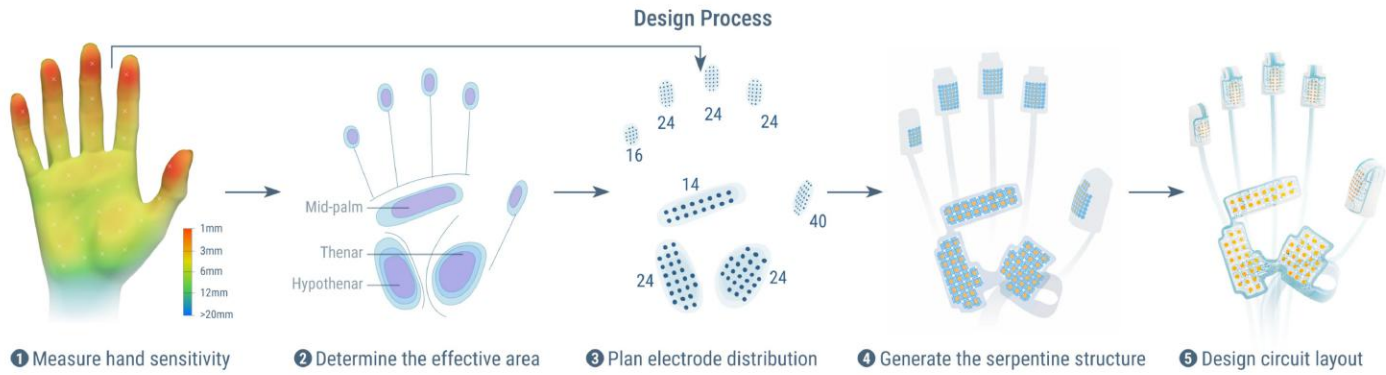
Shape of fingertip FPC

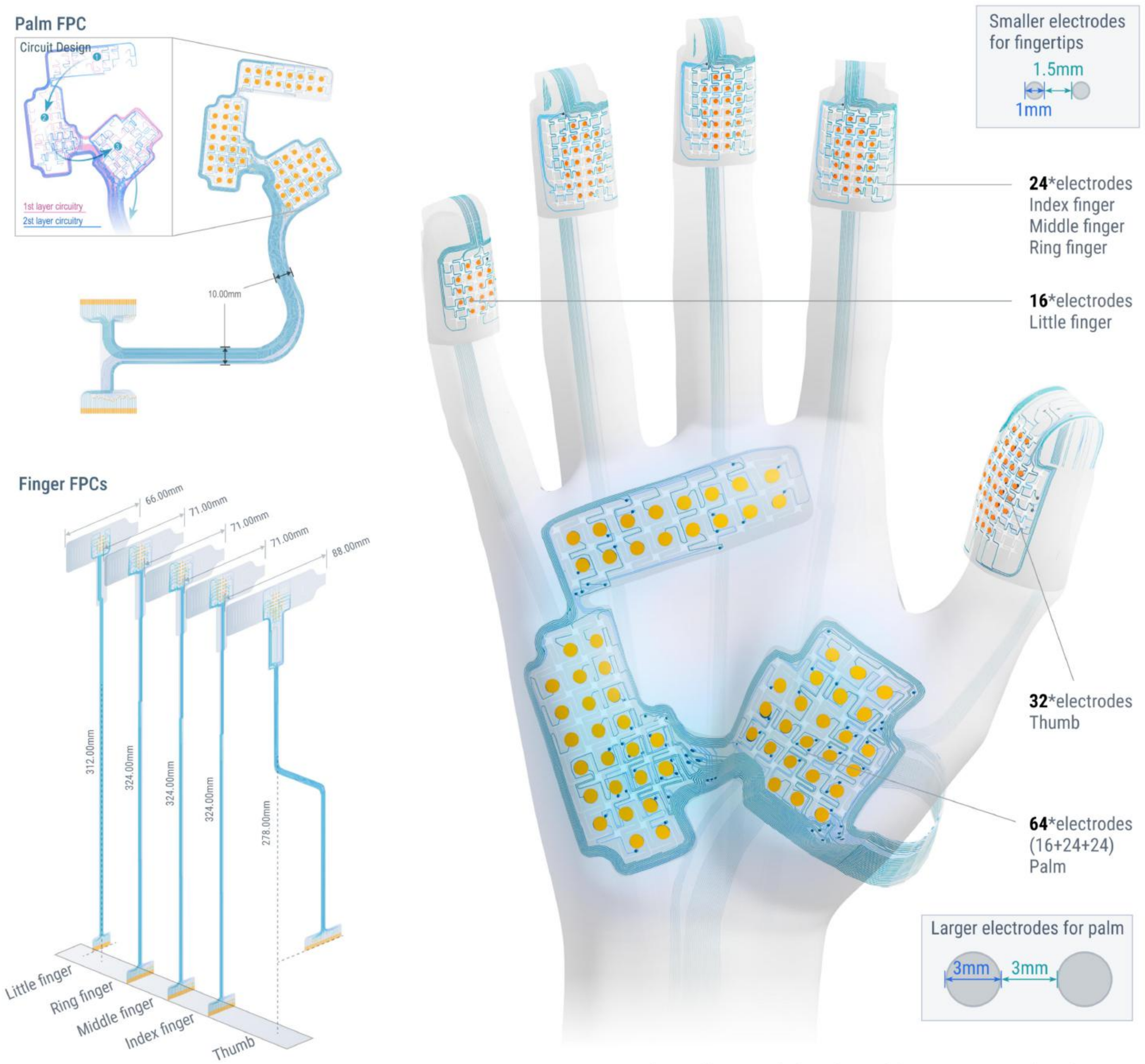
FEA verification



## ■ Development of Full-Hand FPCs for Electrotactile Stimulation

To fully utilize each electrode and achieve precise haptic rendering for the entire hand, I first **defined effective stimulation regions** based on hand-sensitivity tests and then **determined electrode size, density, and layout** accordingly: smaller, denser electrodes for the fingertips and larger, wider-spaced electrodes for the palm. Ultimately, 184 electrode points were arranged within the effective stimulation areas and integrated into six flexible printed circuits (FPCs).



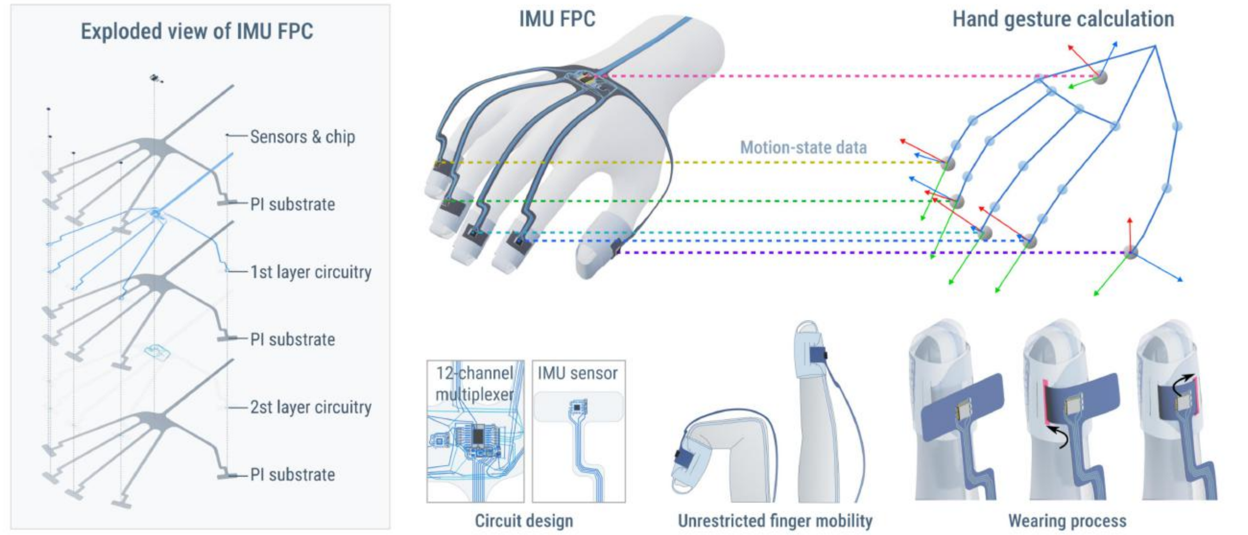




After iterative optimization based on hand ergonomics, the reserved size ensures unrestricted hand movement.

Serpentine structures were designed between all electrodes, and the connecting wires from the electrode points are routed through these structures in an orderly manner, arranged neatly along the dorsal side of the hand, and finally extended to the edge connectors at the wrist.

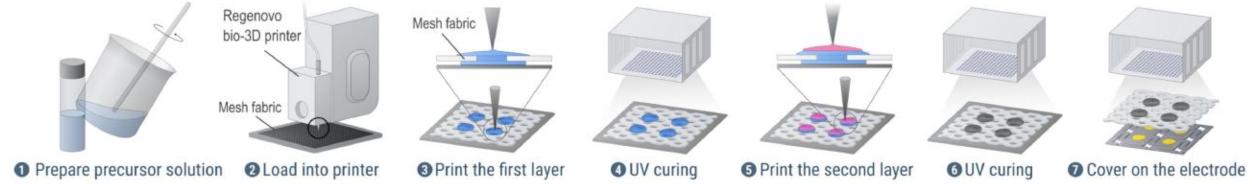
## ■ Addition Layer 1: An FPC Equipped with IMUs

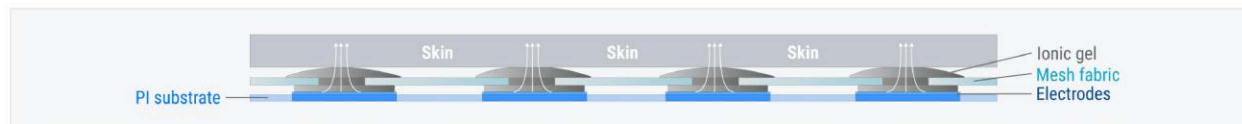
To reliably **capture hand motion**, real-time pose data for each finger is required. We therefore designed an additional FPC layer **integrating a 9-DOF IMU at each fingertip and on the dorsal side of the hand**, while ensuring unrestricted finger mobility. This IMU FPC layer can be fixed by **inserting it into the slot on the haptic FPCs' locking structure.**

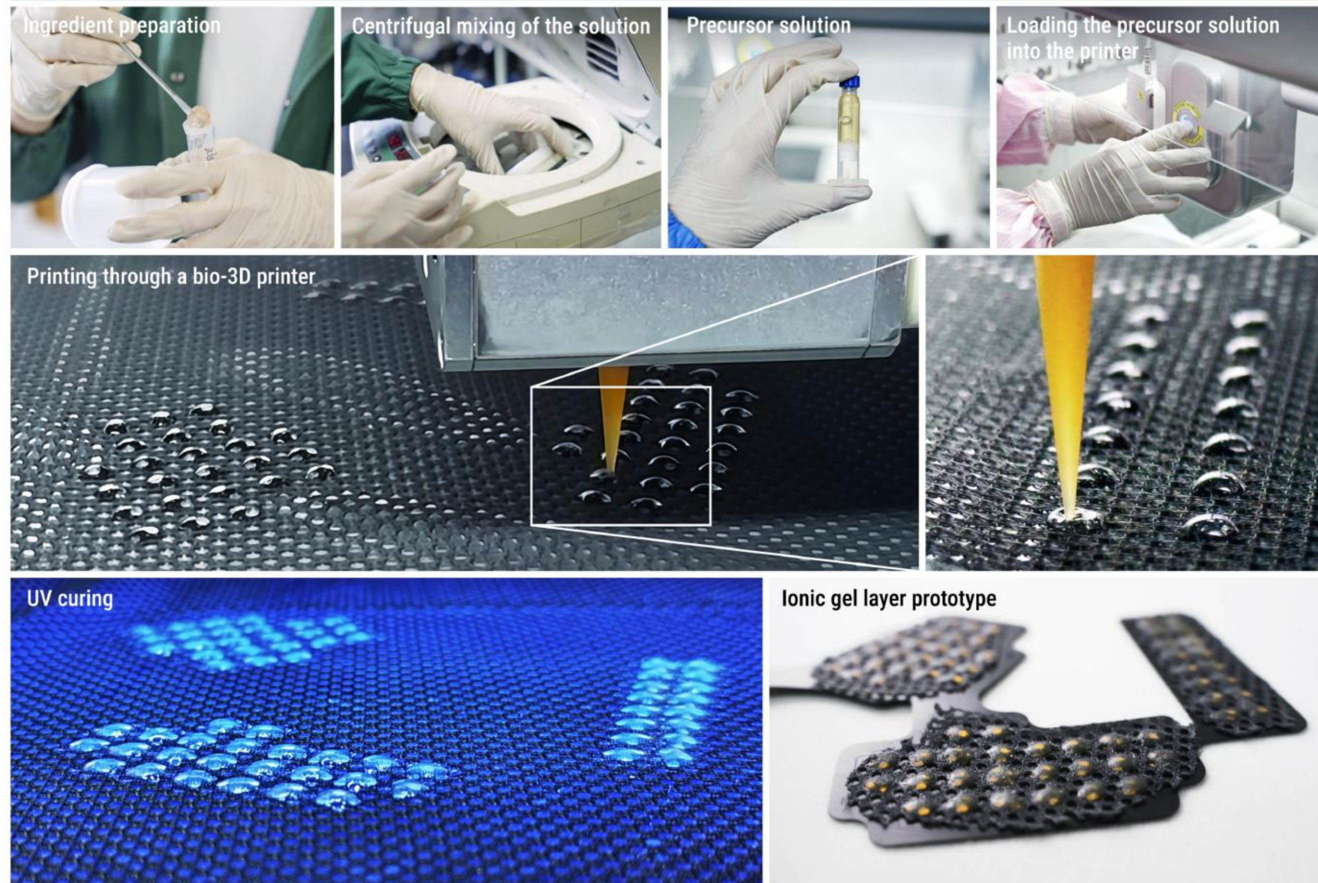



## ■ Addition Layer 2: An Ionic Gel Layer for the Palm

The palm area has many wrinkles, is challenging to fit, and tends to sweat, which not only causes tingling but also accelerates electrode oxidation. We developed **a new fumed-silica ionic-liquid gel**. Using a biological 3D printer, the gel was printed onto mesh material according to the palm electrode layout and then applied to the palm FPC. This additional layer **ensures stable adhesion to the skin, softens the stimulation sensation**, and prevents direct sweat–electrode contact, **effectively slowing electrode oxidation.**



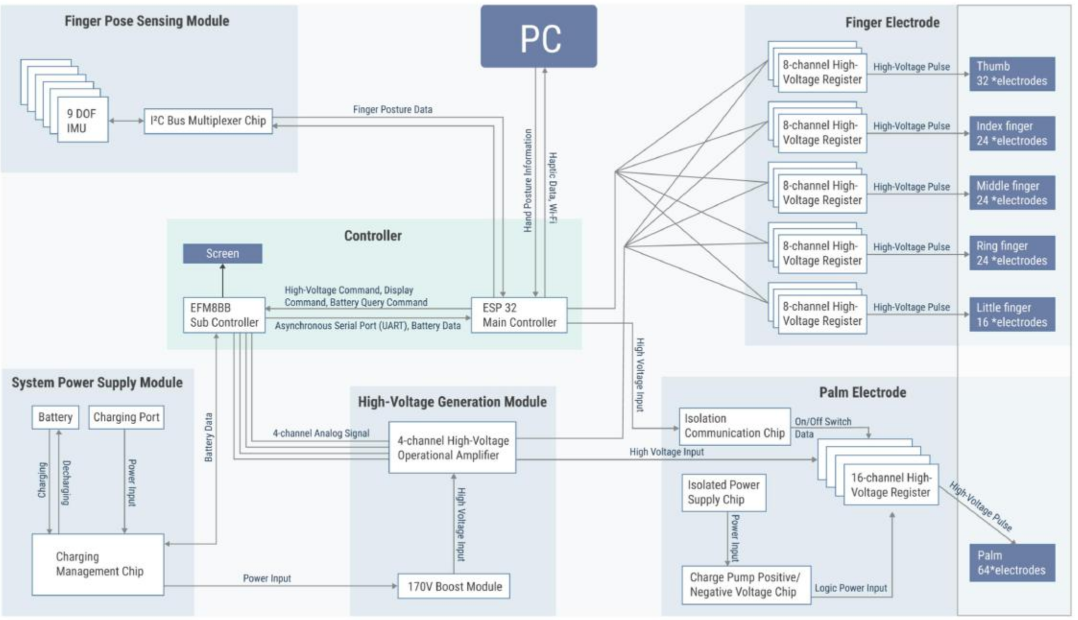



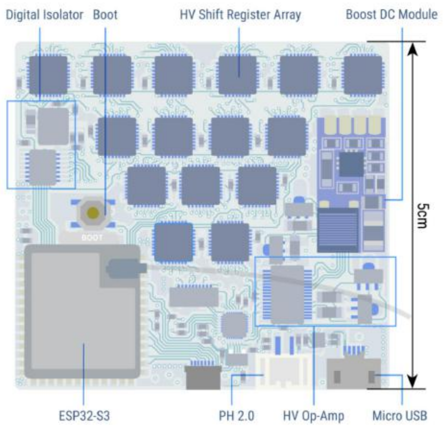
## Small PCB Driver Board

The driver board used in earlier experiments measured 20×20×5 cm, which was far too bulky for wireless wearability. After several engineering iterations, the entire system was **compressed to approximately 5×5×1 cm**, allowing it to be worn comfortably on the wrist. This compact driver can control 184 electrode points with **three electrical states** (high impedance, high voltage, and low voltage). It also receives finger-pose data and includes a Wi-Fi module for communication with a PC.

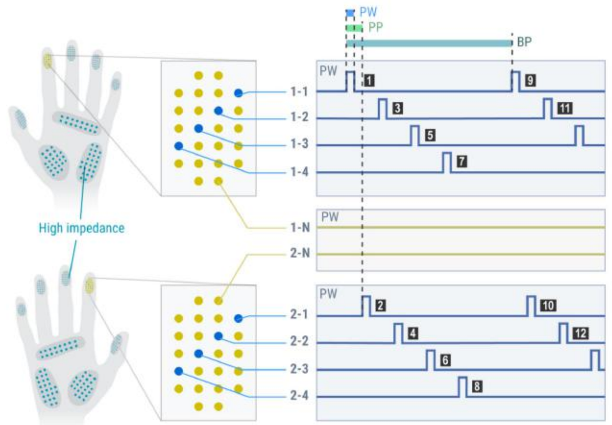
Small Driver System's Architecture



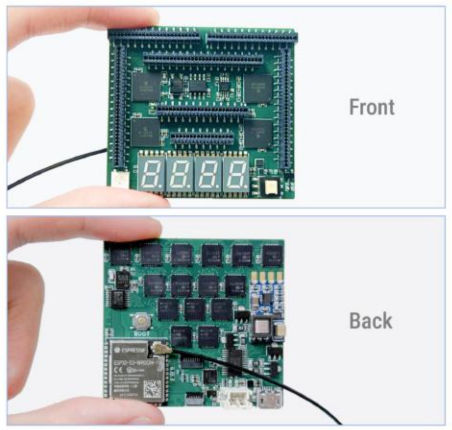

Hardware Layout

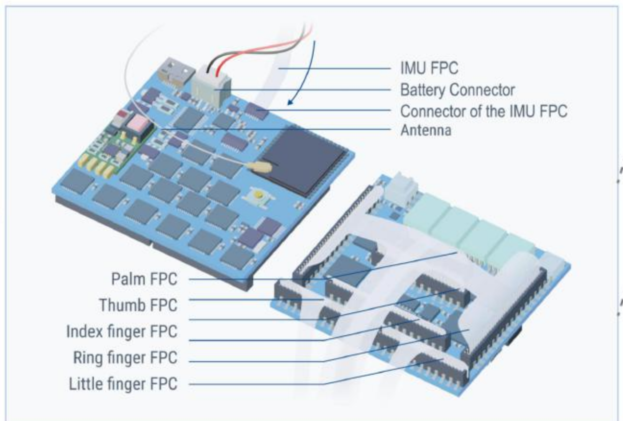



Electrode Control Scheme



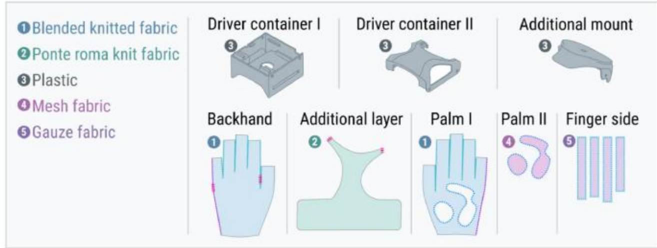

Four nixie tubes on the front of the driver provide real-time scrolling voltage readouts, and seven FPC connectors allow attachment of the six electrotactile FPCs. The back of the module houses components such as the Wi-Fi antenna, high-voltage module, and an IMU FPC connector.

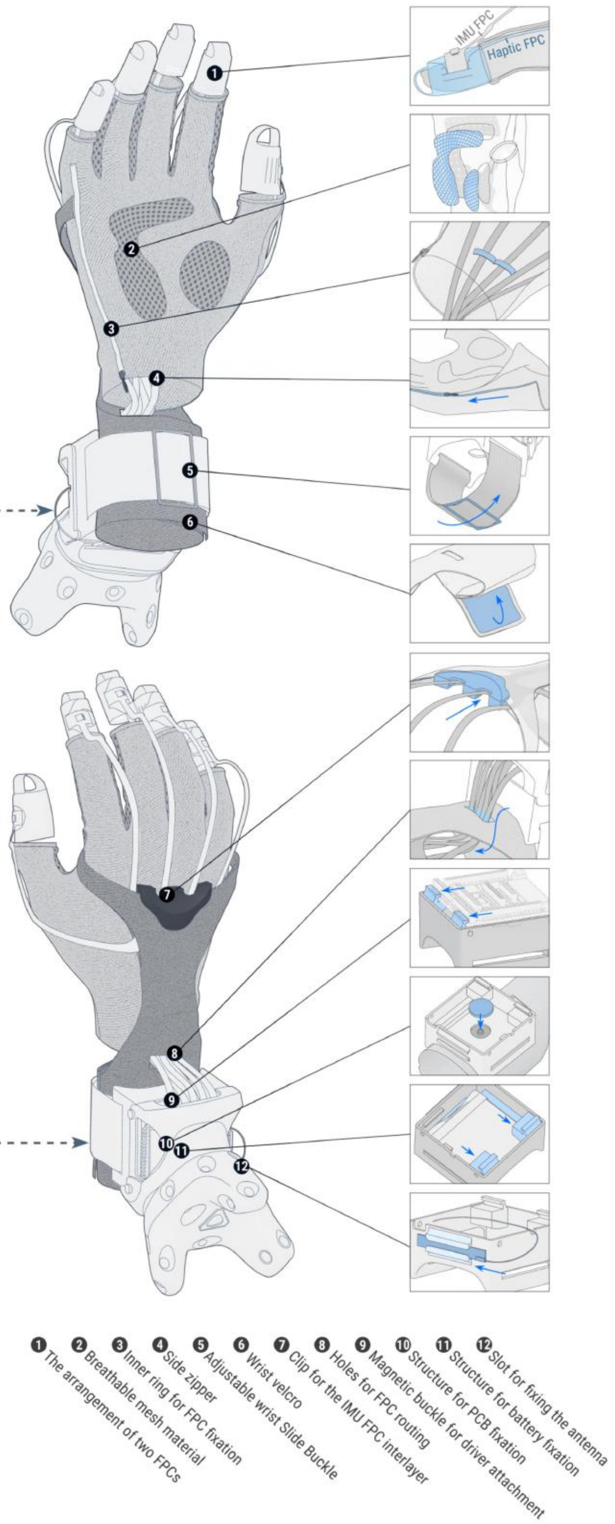


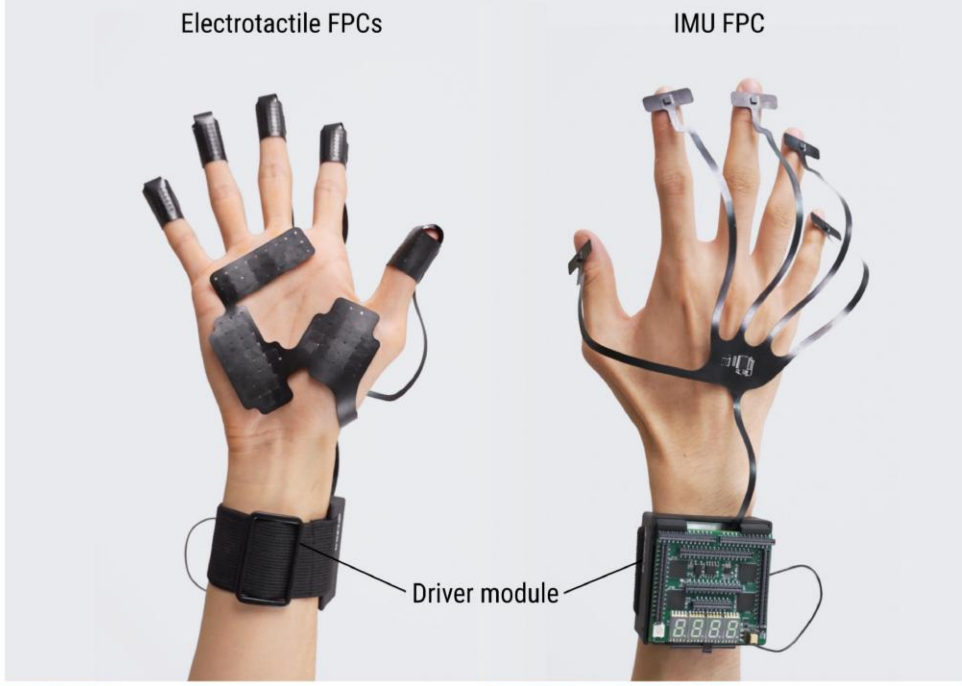

## Fabric Layer and Driver Board Container

The glove's fabric layer has undergone multiple rounds of testing and refinement to ensure **breathability in the palm and a secure, comfortable fit**. Its structure holds all FPCs firmly in place while allowing easy removal and replacement. The wrist shell, which houses the driver and battery, is 3D-printed and includes an additional mount designed for attaching the HTC VIVE Tracker.




## FPCs and Structural Wearability Testing

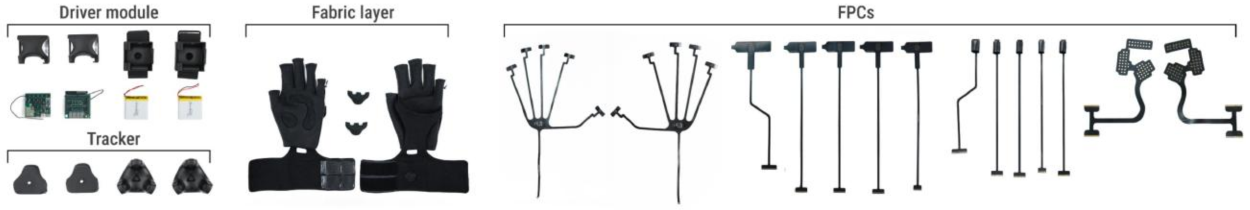


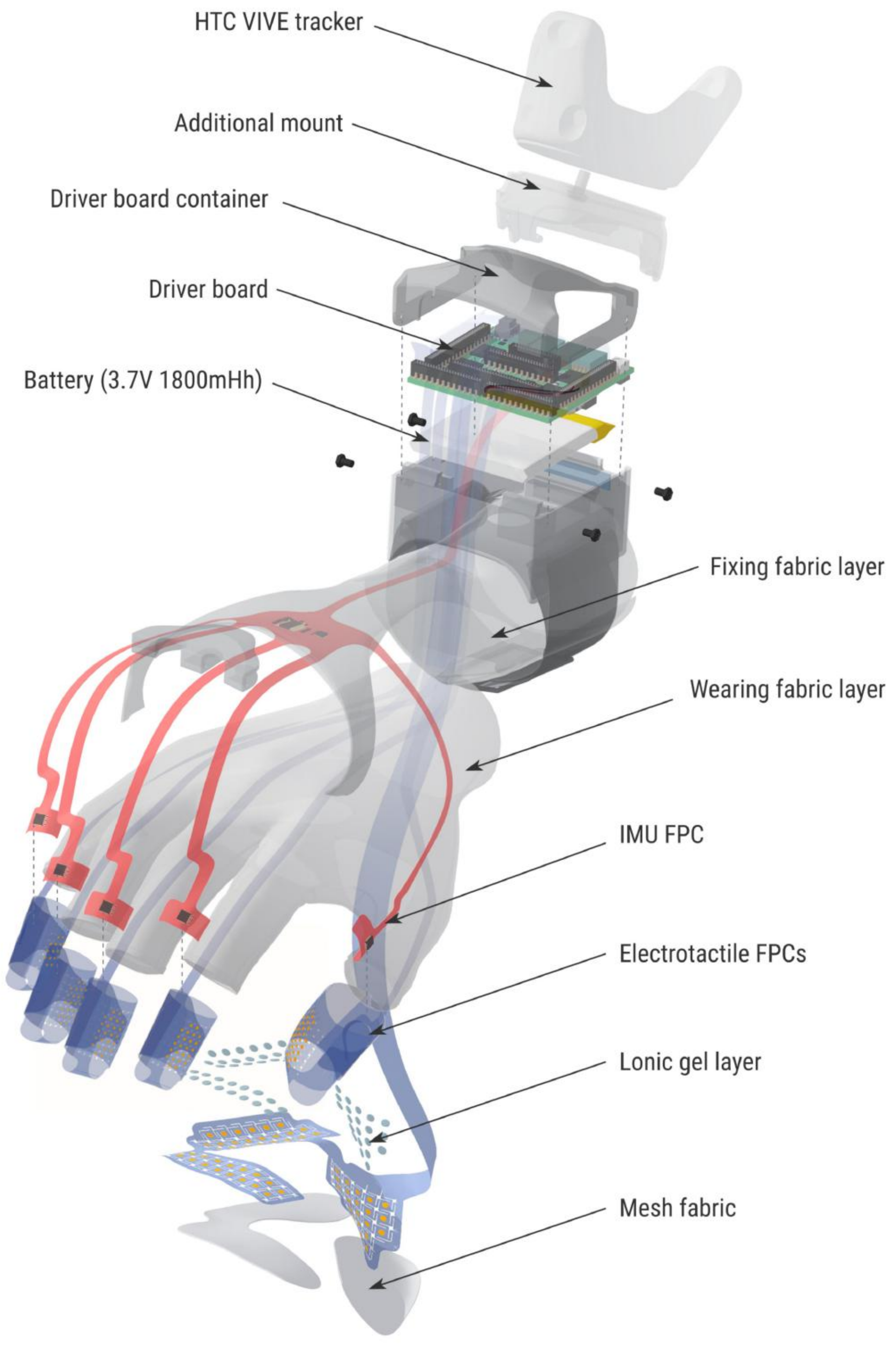





## Exploded View

EXILO consists of four parts: the fabric layer, FPCs, driver module, and the additional HTC VIVE Tracker.




EXILO is currently **the lightest, most precise, and most cost-effective wearable haptic device on the market**. It integrates 184 stimulation points, weighs only 120 grams (excluding the tracker), and can be manufactured for approximately $180, far lower than existing devices that cost thousands of dollars. With these advantages, EXILO has the potential to make high-quality haptics more accessible in everyday VR applications.






## Applications

EXILO applies across many fields.

**A Teleoperation**
For teleoperation tasks, EXILO provides real-time haptic feedback from robotic arms, reducing errors and enabling delicate, previously impossible actions.

**B VR Gaming and Life**
EXILO also renders rich material sensations, ranging from the roughness of rock to the softness of fabric, and enhances users' perception of object shape, creating deeper immersion in VR gameplay.

**C Surgical Training**
In VR surgical training, EXILO delivers precise feedback on tissue stiffness and applied force, improving both accuracy and learning efficiency.

## Frontier

As the first inventor, I founded my company, **Frontier,** based on this technology. I now serve as its co-founder and CTO, focusing on developing sensory-augmentation and rehabilitation technologies.

CEO Qingyun Zheng | CTO Hongyu Yue | COO Ruiyi Liu

OSCARS x12

Qualifying Festival for the Academy Award

04

# Urban Duo

## A Stylized Animation Comparing Longchang Apartment and the City of Shanghai

Shanghai is a fast-paced, highly modernized city. However, the Longchang Apartment within it stands out for its distinctive, nostalgic environment, rich everyday atmosphere, and warm, close-knit relationships within the neighborhood. I created a six-minute stop-motion-style animation using 3D techniques. Through cubic compositions and dual-screen parallel storytelling, it contrasts the living environment, interpersonal relationships, and attitudes toward life between Longchang Apartment and the broader city of Shanghai.

*September 2023 – February 2024*
*Tongji University, Shanghai, China*

[https://youtu.be/4yJ3GsRyo74](https://youtu.be/4yJ3GsRyo74)

## Individual Project

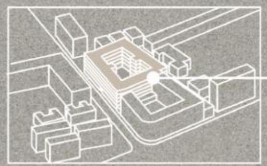
**Keywords**
Character Animation; Stop-Motion-Style Rendering; Community Culture

**Instructor**
Prof. Yinan Zhang, Director of Media and Communication Department, Tongji University

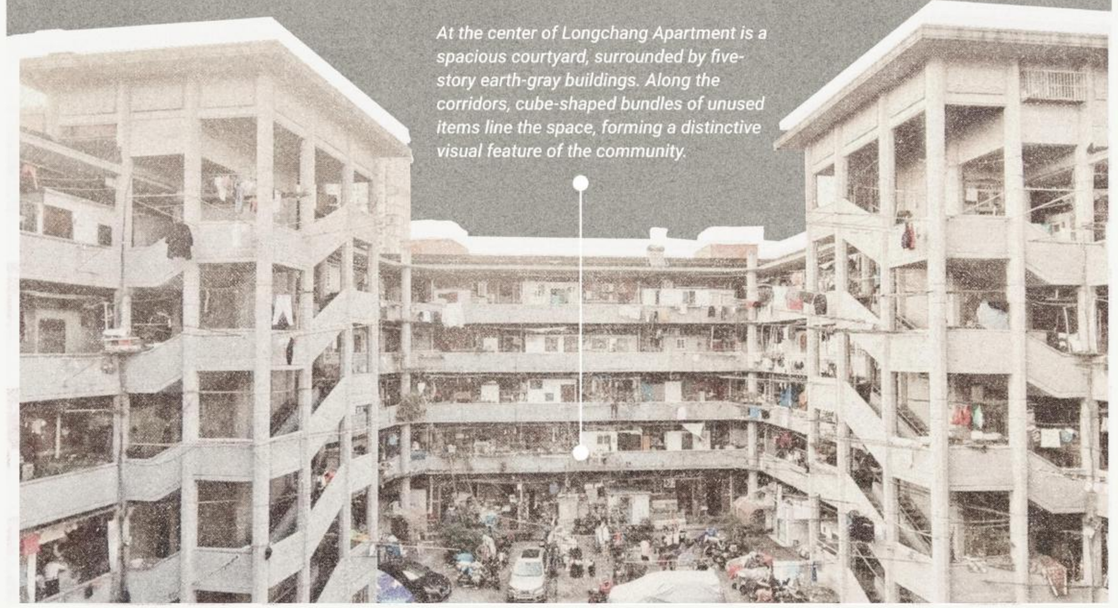
**Achievements**
Officially selected at 31 international film festivals, including 12 Oscar-qualifying festivals such as PÖFF Shorts 2025 and Animafest Zagreb 2025 (the world's top-tier animation festivals). Secured 4 awards, including the Best Animated Film, Best Student Animated Film and Best Artistic Award

## Inspiration

Passing by ***Longchang Apartment***, I was struck by its vivid sense of everyday life. The old furniture and warm interactions among neighbors made me feel as if I had stepped back into the last century. In a time when urban relationships are increasingly distant, this atmosphere feels especially precious.



*Longchang Apartment is located at No. 362 Longchang Road, Shanghai.*



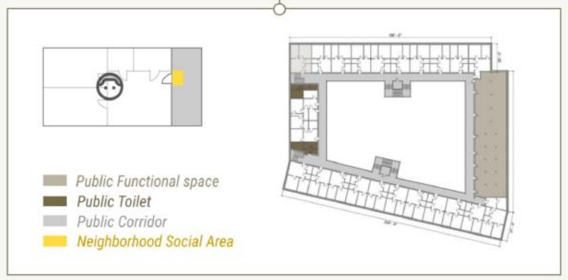
*At the center of Longchang Apartment is a spacious courtyard, surrounded by five-story earth-gray buildings. Along the corridors, cube-shaped bundles of unused items line the space, forming a distinctive visual feature of the community.*

## Why does Longchang Apartment look like it was forgotten in the last century?

*Source: Yang, F. (2016). A Reexamination of the Transformation of Old Residential Forms: A Case Study of Shanghai Longchang Apartments. Times Architecture, (6), pp. 34-43.*

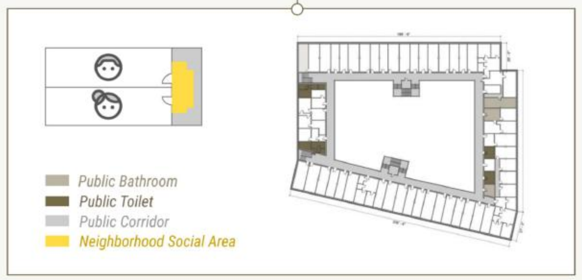
### 1933-1949

*The apartment was originally built as a police dormitory in the former Shanghai Public Concession, with a layout designed for easy supervision, where each unit housed only one person.*




### 1949-1980

*Later, the facility was converted into staff dormitories. As the population increased, units were subdivided, and some public areas were transformed into living spaces.*




### 1980-NOW

*Longchang Apartment gradually became available for rent, and the density of residents soon exceeded the building's intended capacity. Illegal housing expansions became increasingly common.*


Over time, long-term tenants maintained their old habits while compressing unused items into ***space-saving cube forms***. As the population continued to grow, limited space led private areas to gradually encroach upon public corridors. Push open a door, and ***countless cube-shaped bundles and scenes of everyday neighborhood life*** unfold, creating a unique living landscape reminiscent of the last century.

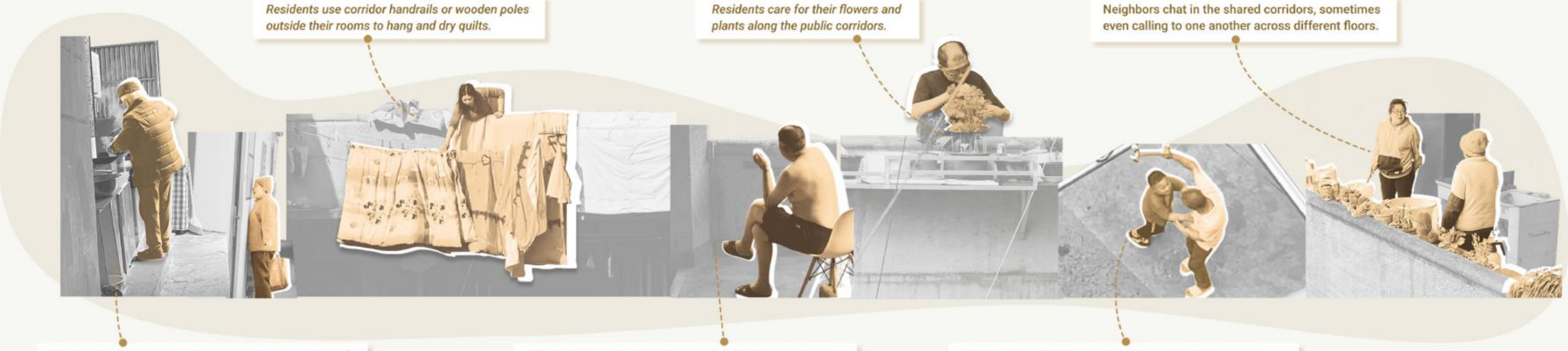
## What's so special about life at Longchang Apartment?

**Blurring the boundaries between private and public space, Longchang Apartment fosters a unique living landscape that shapes residents' lifestyles and ways of thinking.**

*Residents use corridor handrails or wooden poles outside their rooms to hang and dry quilts.*

*Residents care for their flowers and plants along the public corridors.*

Neighbors chat in the shared corridors, sometimes even calling to one another across different floors.



Cooking happens in shared spaces, where the sizzle of frying and the smell of food fill the entire apartment.

*Elderly residents stand in the corridors, basking in the sun as they look across the courtyard at the opposite buildings.*

The sounds of children and adults playing in the open ground-floor area drift up to everyone living in the building.

*Wang Ailan*
*79 years old*

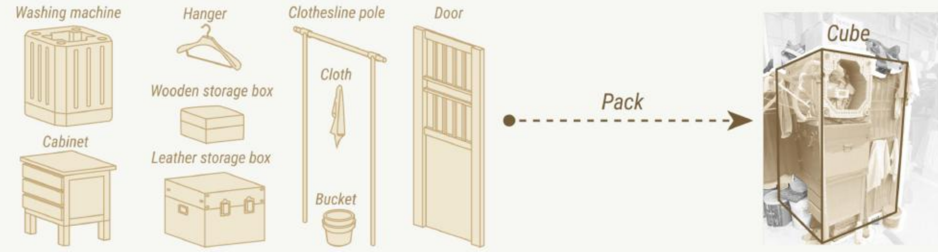
*Came to Shanghai in 1959 to get married and lived in Longchang Apartment until today.*

"It's a pleasant and convenient place to live. Chatting with neighbors or meeting someone on the way to the grocery store ***always feels warm and reassuring***. Once, a neighbor even saved my husband's life. When I lived elsewhere in the city, the doors around me stayed shut. I didn't even know my neighbors' names. What truly matters is ***human connection***; material wealth was never something we thought much about."

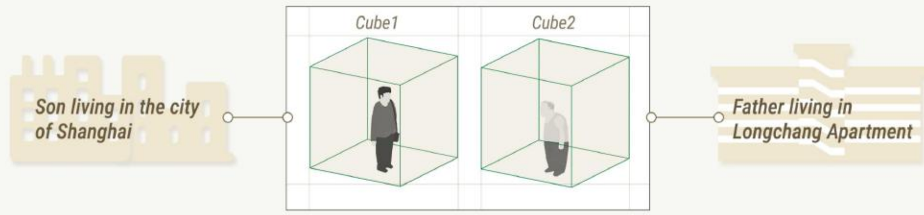
In Shanghai's fast-paced urban environment, social ties have grown increasingly distant. Even so, Longchang Apartment, located right in the city, continues to preserve the ***spirit of old lane culture***, characterized by ***frequent interactions, familiar faces, and strong community bonds***. Here, residents lead peaceful and grounded lives, placing greater value on human connection than on status or wealth.

## Project Direction: 3D Animation

***1. Cube-Formed Narrative:*** With limited interior space, residents naturally compress unused items into ***cube-shaped bundles***, forming a unique visual language of the apartment. I therefore adopted the cube as the core formal language of the animation.

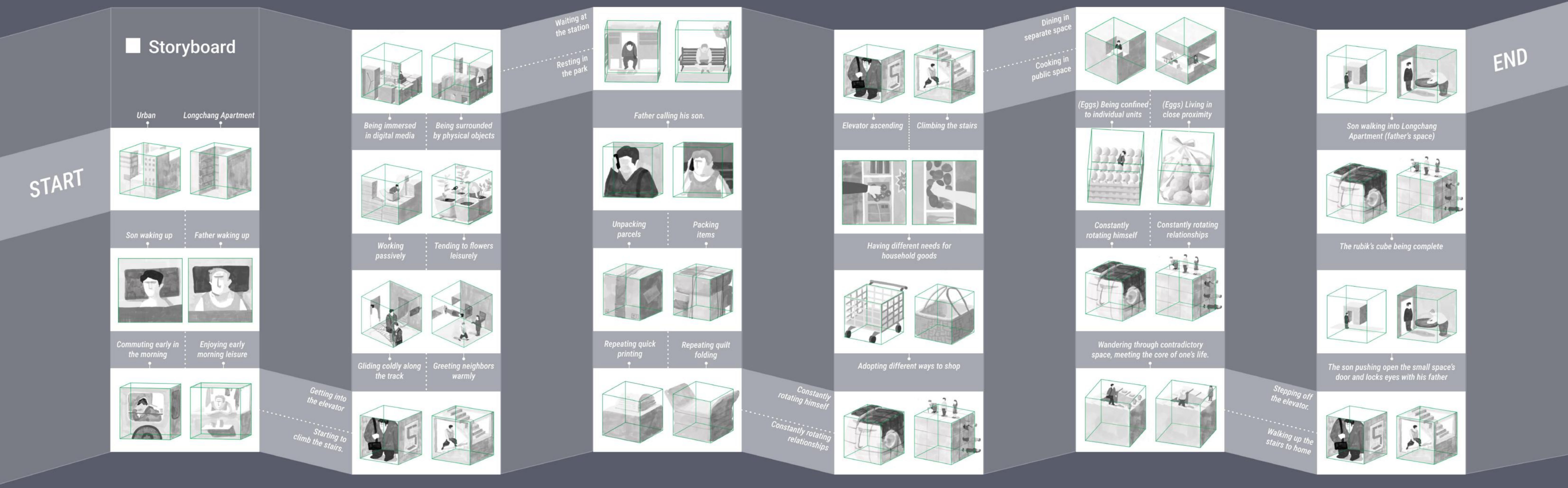



***2. Dual-Screen Animation:*** By comparing the two sides, I aim to highlight the similarities and differences in ***living environments, interpersonal relationships, and life attitudes*** between Longchang Apartment and the city of Shanghai.

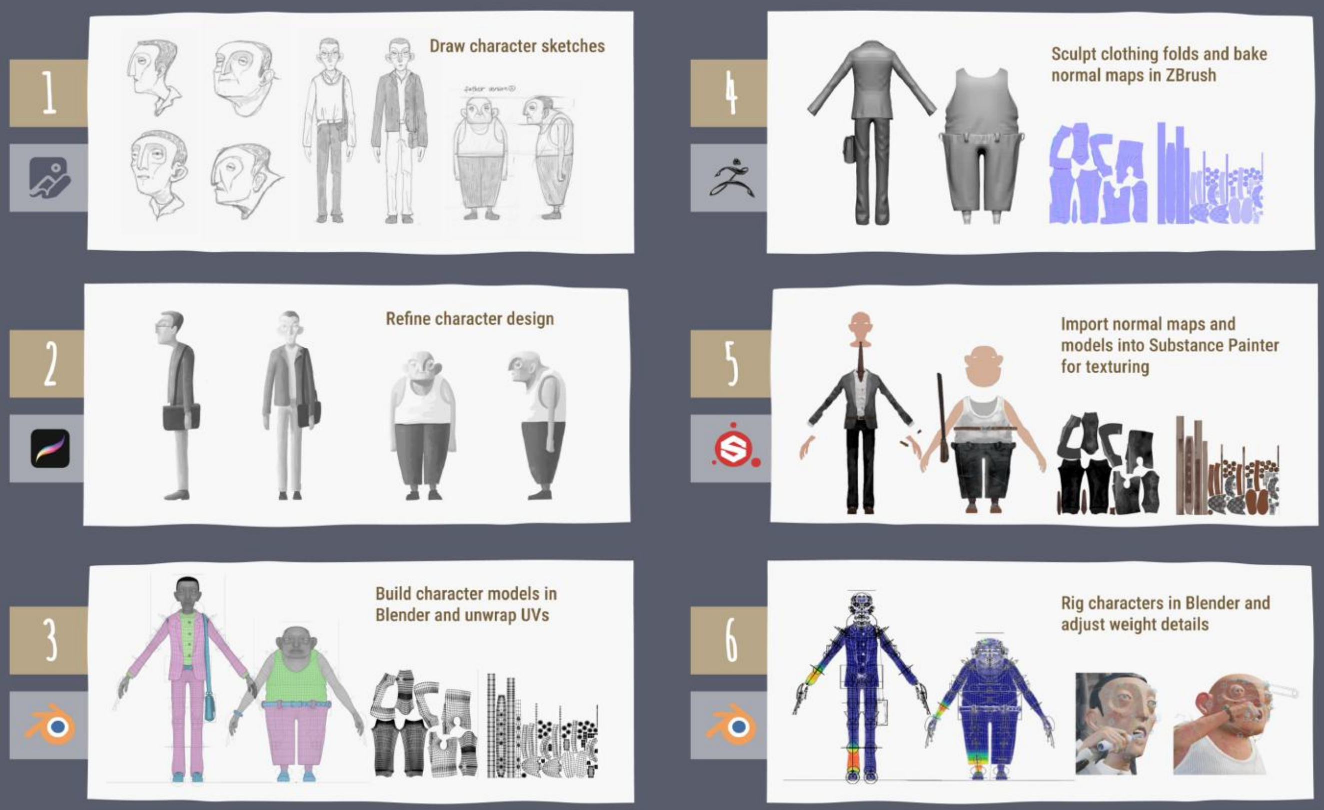


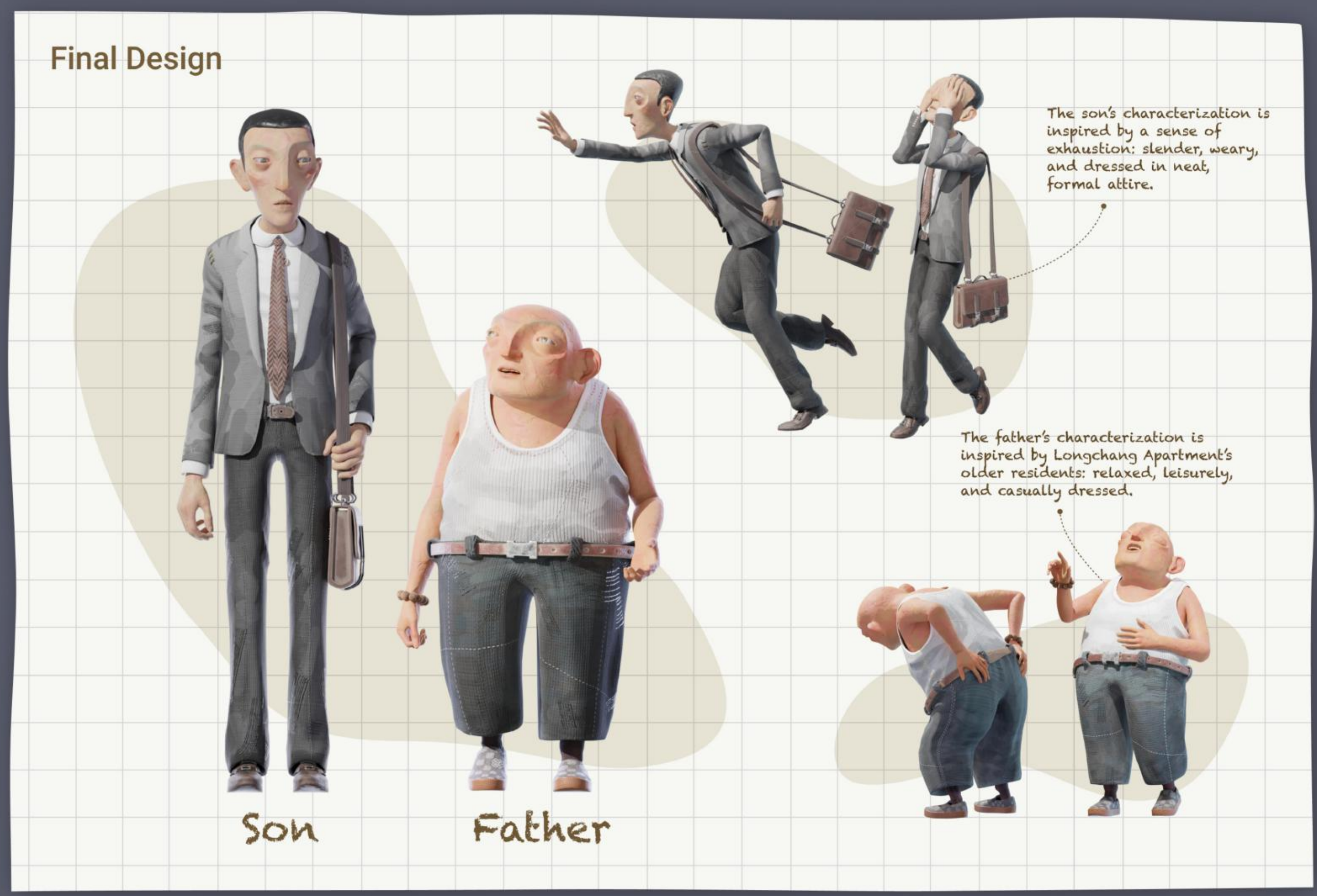

***3. Stop-Motion Stylized Rendering:*** The lively everyday atmosphere of Longchang Apartment aligns naturally with the ***handmade quality of stop-motion animation***. I used stylized rendering to simulate this stop-motion's visual effect, constructing the cubic scenes from everyday materials.

## Storyboard




## Character Design



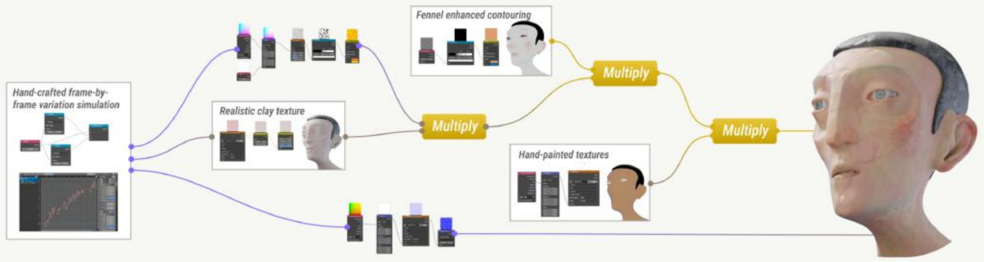
## Stop-Motion Stylized Rendering

The vintage, simple, and humanistic stylized effect of stop-motion animation aligns perfectly with the nostalgic atmosphere of Longchang Apartment. By researching stop-motion materials and conducting extensive stylized rendering tests, I developed a ***3D technical workflow to recreate realistic stop-motion scenes and frame-skipping effects.***



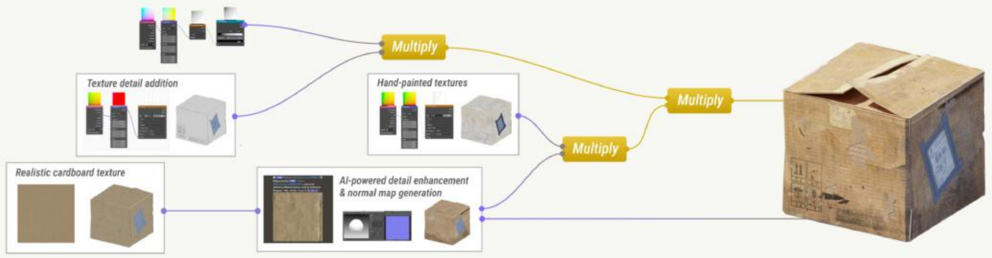
### Dynamic Texture

Clay is often used for moving objects, with its surface texture changing as the shape is adjusted frame by frame. I applied realistic clay textures to the characters' skin and hair to recreate this dynamic effect.



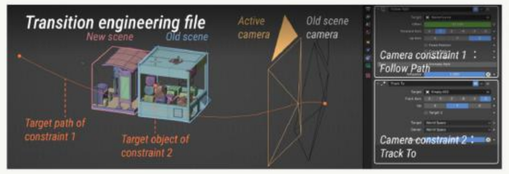

### Static Texture

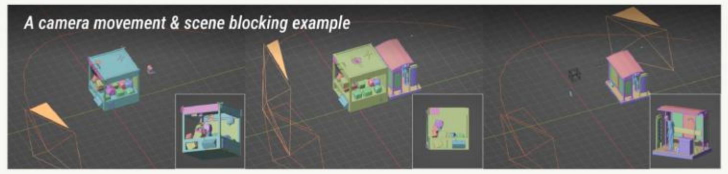
Cardboard textures were used for environmental elements and props such as beds, tables, and flowerpots. Following authentic stop-motion production methods, I added hand-painted details to enhance their distinct material qualities.

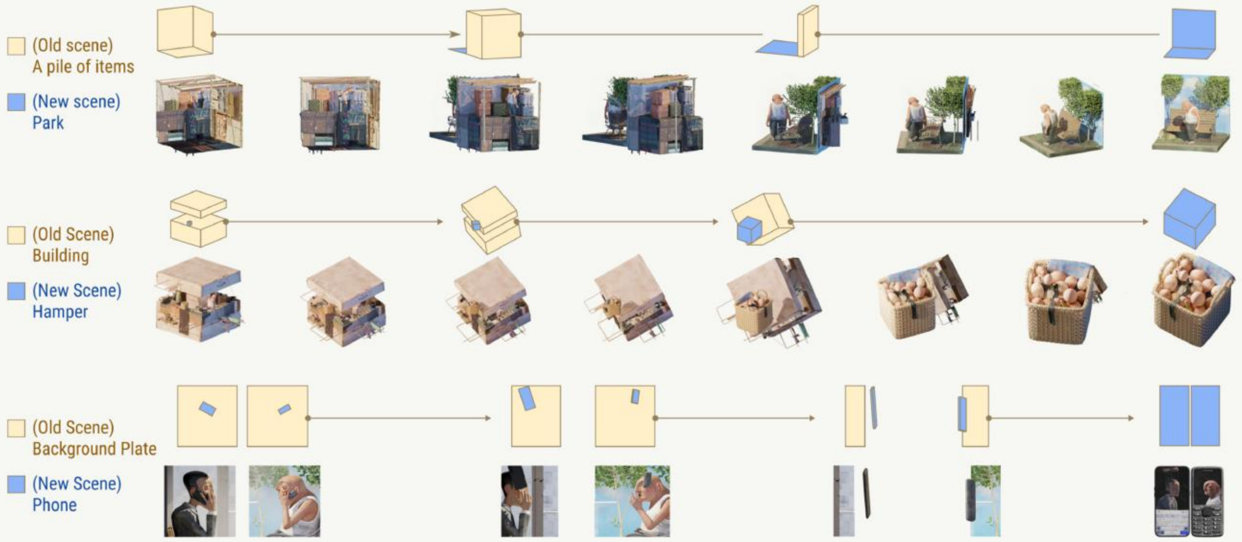



## Geometric Spatial Transition

The animation adopts an orthographic perspective, with transitions between selected shots. By ***transforming cubes geometrically to bridge two scenes***, it produces transitions that resemble ***spatial illusions***. Each transition is created in a separate project file containing the start and end frames of the incoming and outgoing scenes.

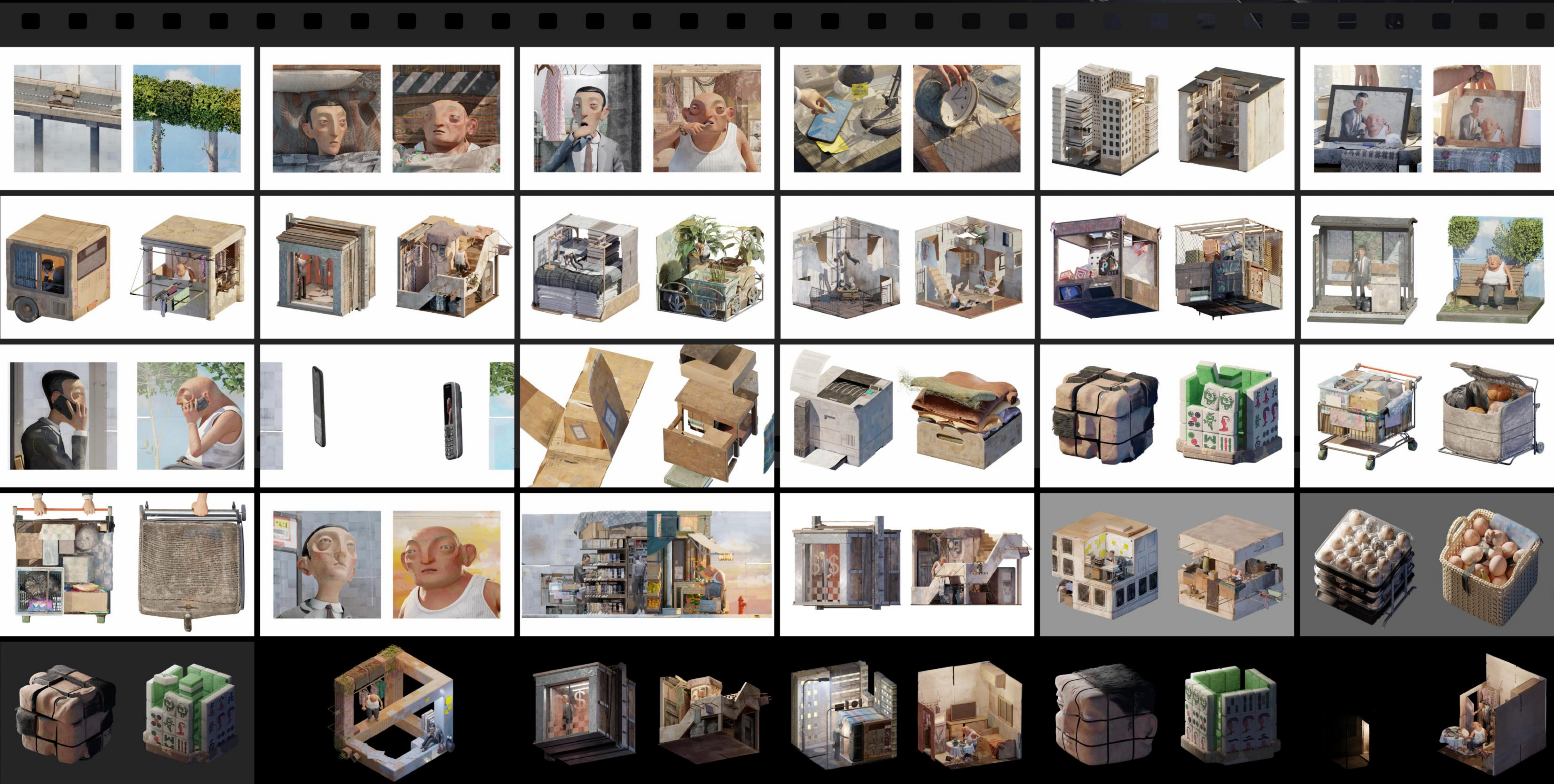


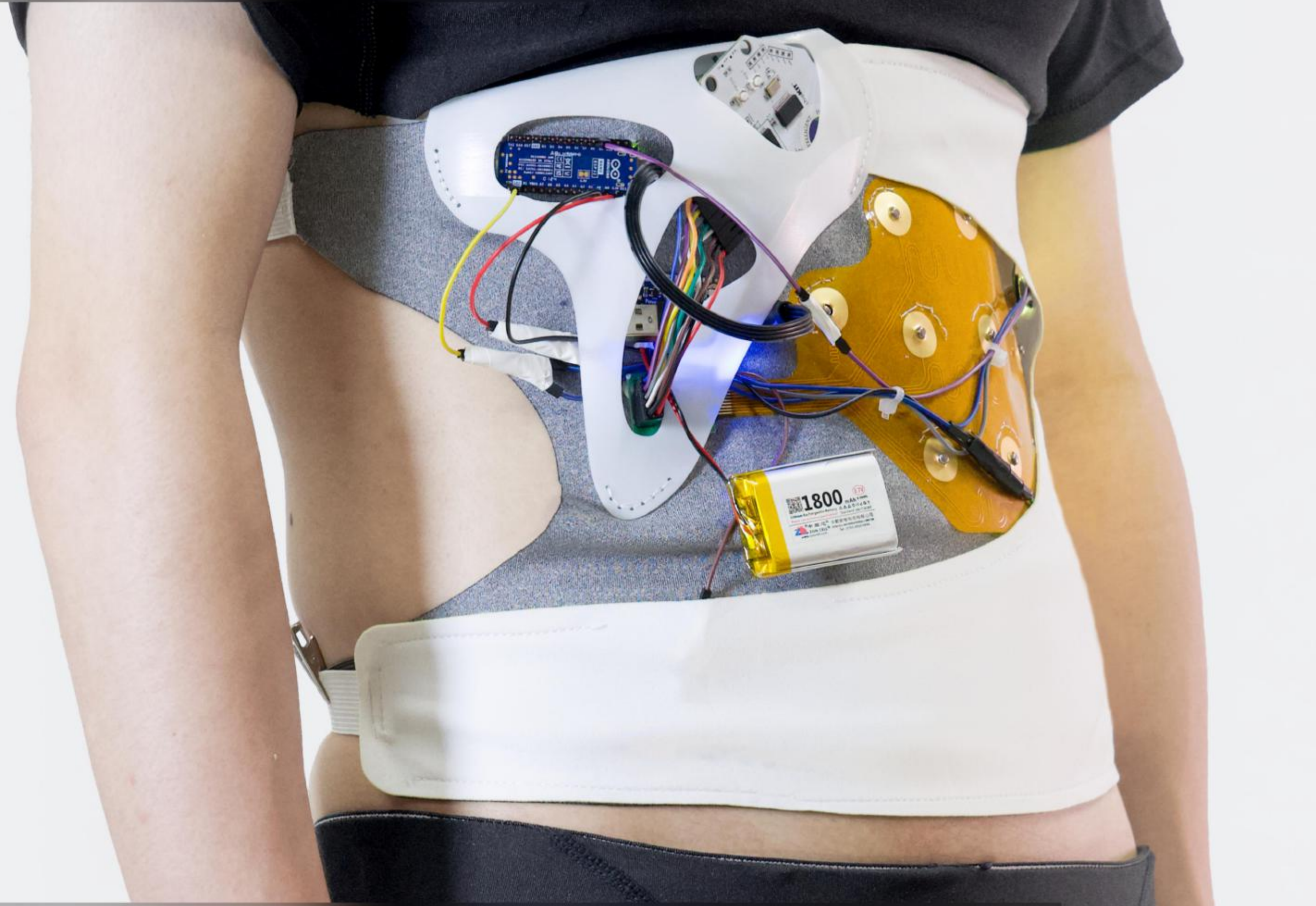

OFFICIAL SELECTION x31 HONORABLE MENTION x4 AWARD WINNER x4 OSCARS Qualifying Festival for the Academy Award x12

Urban Duo has been officially selected by 31 international film festivals, including 12 Oscar-qualifying events such as PÖFF Shorts 2025 and Animafest Zagreb 2025. It has received 4 awards, including Best Animated Film, Best Student Animated Film, and Best Artistic Award.

## Individual Project

**Keywords**
Gut-Brain Axis; Wearable Device; Physiological Signal Monitoring; Future Product




05

# ZenBelly

## A Wearable Device for Maintaining Gut-Brain Axis Health

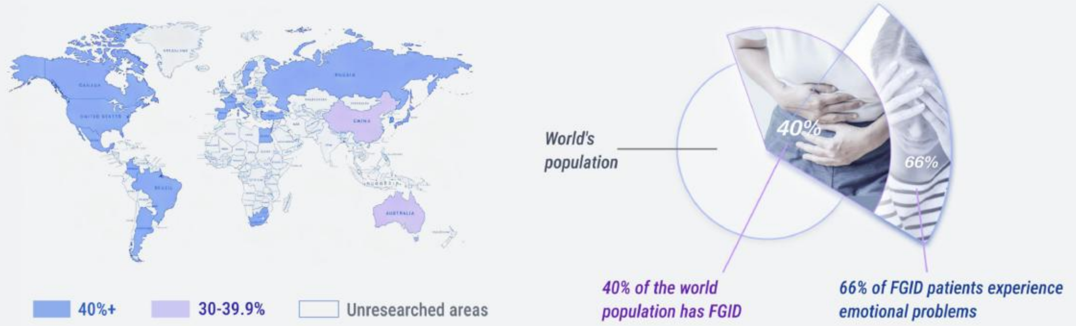
ZenBelly is a wearable device designed for individuals with gastrointestinal disorders, supporting gut-brain axis health by predicting and regulating both gastrointestinal disorders and emotional problems. Because of the bidirectional communication of the gut-brain axis, gastrointestinal disorders are often accompanied by anxiety, depression, and other emotional problems, an association that is frequently overlooked in treatment. Simultaneous regulation of both gastrointestinal and emotional problems can lead to significantly better outcomes. ZenBelly uses non-invasive monitoring of physiological signals to evaluate gastrointestinal status and emotional risk continuously, and provides timely, targeted regulation to address these issues more effectively.

*https://youtu.be/DOpJmoCMnBA*

*April 2024 – June 2024*
*Tongji University, Shanghai, China*

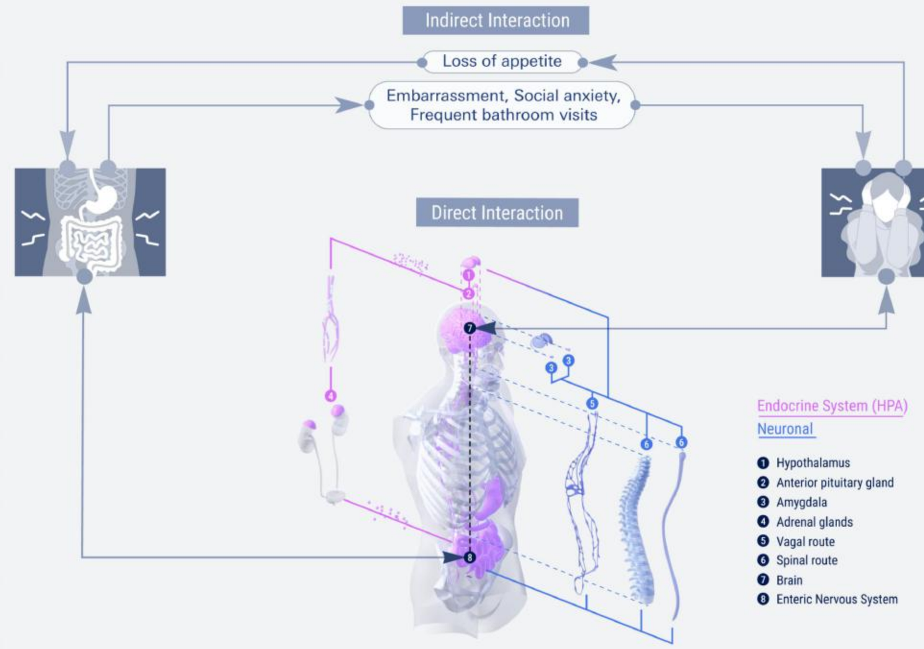
## ■ Problems

A recent study involving 73,076 participants from multiple countries found that **more than 40%** of the global population suffers from **functional gastrointestinal disorders (FGID)**. Many individuals with gastrointestinal disorders also experience significant emotional changes. The research shows that nearly **two-thirds** of these patients have **emotional problems** such as anxiety and depression, far higher than the normal level.




## ■ Analyse

The gut is often referred to as the "second brain." The nervous systems of the brain and the gut are closely connected through a complex **bidirectional communication pathway**. When gastrointestinal disorders occur, the gut sends signals to the brain and triggers emotional problems; in turn, negative emotions may further aggravate gastrointestinal disorders, forming a **vicious cycle**. Simultaneously monitoring and regulating both emotion and gastrointestinal status can lead to more effective treatment outcomes.




## ■ Interviews

**Patient1**
Chuheng He, 24
Artist

*Sometimes, when I experience gastrointestinal (GI) discomfort, emotional fluctuations tend to arise suddenly.*

Symptoms are unpredictable

**Patient2**
Zhan Lu, 22
Undergraduate

*Under academic pressure, I sometimes suffer from diarrhea, and by the time I start taking medication, it is often too late.*

Failure to intervene in time

**Expert**
Xiang Song, 47
Gastric Expert

*Emotional stability is often the foundation for easing GI disorders, yet it's easily overlooked. A holistic approach is needed to treat both emotional and GI disorders issues effectively.*

Holistic treatment approach

| | | |
|---|---|---|
| Early detection of emotional risk before symptom onset | Portable wearable devices for timely intervention | Regulating both emotional problems and GI disorders simultaneously |

**Opportunities**

## Project Direction

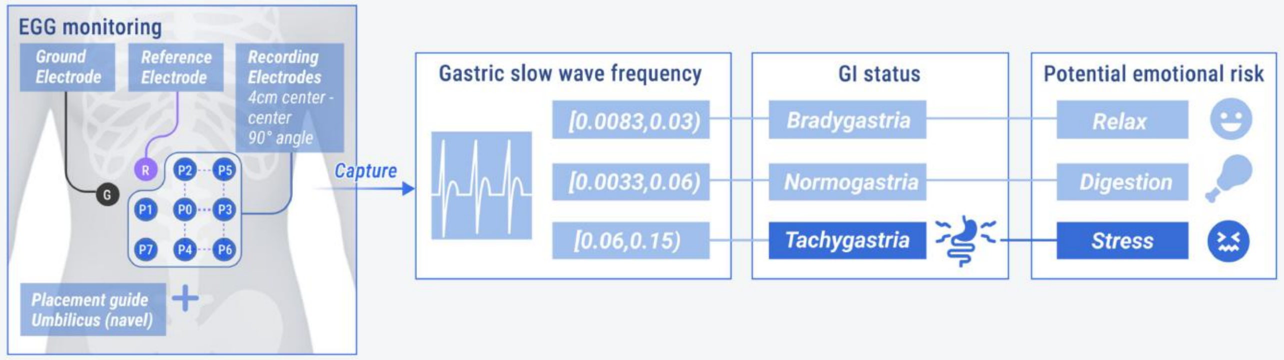
**A wearable smart device can monitor gastrointestinal status, analyze accompanying emotional risk, and deliver timely regulation.**

| Monitoring & Risk Alerts | Regulation & Treatment | |
|---|---|---|
| Real-time monitoring of gastrointestinal abnormalities and analysis of accompanying emotional risk | Preventing emotional problems | Relieving gastrointestinal discomfort |
| Monitor gastric slow waves with non-invasive electrogastrography (EGG) | Guiding abdominal breathing through stretch sensor | Stimulating acupoints with electrical pulses |

## Approach

### Status Monitoring

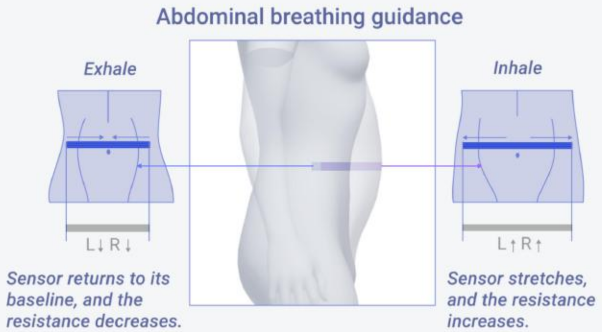
Building on research into gastrointestinal disorders and emotional problems, I plan to use **non-invasive electrogastrography (EGG)** to monitor the condition of the gastrointestinal tract, predict emotional risk, and issue early warnings. To capture **gastric slow waves** required for EGG analysis, I designed **an abdominal wearable system equipped with 10 electrodes.**

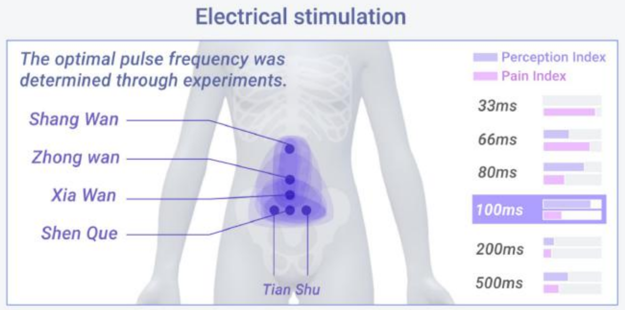



Source：Vujic, A., Tong, S., Picard, et al., (2020). Going with our Guts: Potentials of Wearable Electrogastrography (EGG) for Affect Detection. In: Proceedings of the 2020 International Conference on Multimodal Interaction. New York: Association for Computing Machinery, pp.260-268.

### Timely Regulation

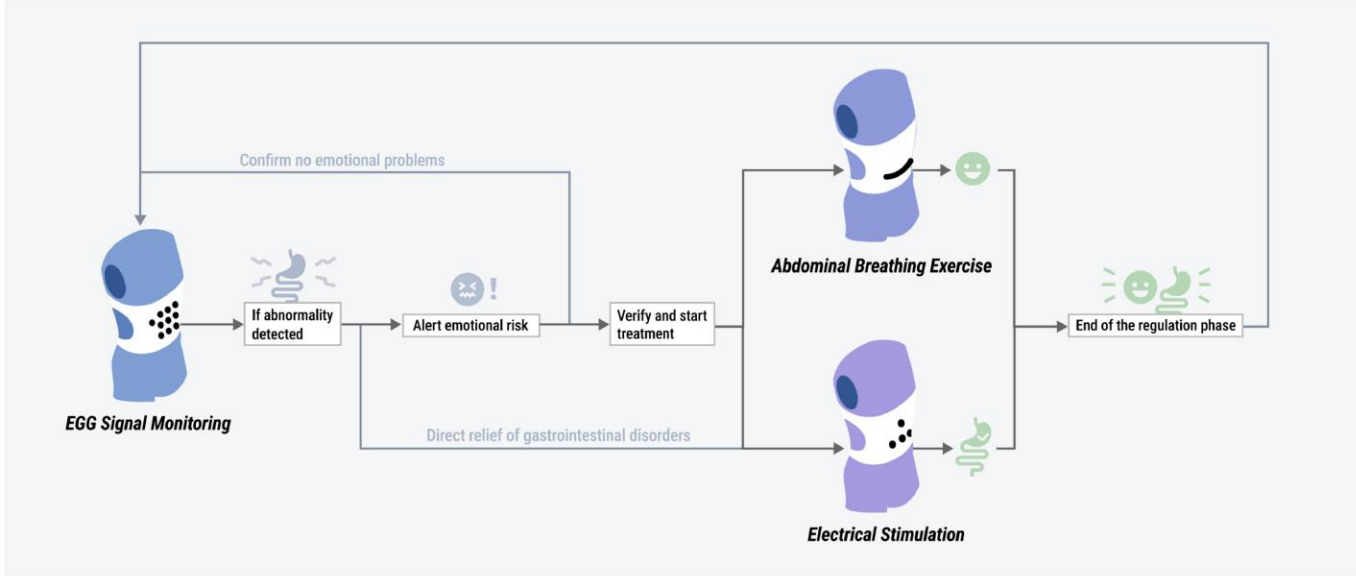
**Abdominal breathing** is an effective method for rapidly relieving emotional problems, and **stimulating specific acupoints** is a commonly used approach for regulating gastrointestinal disorders. To guide abdominal breathing, a **stretch sensor** is placed on the abdomen; the sensor's resistance changes with respiration, allowing the system to monitor breathing patterns in real time and provide targeted guidance. For gastrointestinal regulation, acupoints with proven effectiveness and mild sensation were selected, and **electrical stimulation** was applied for treatment.



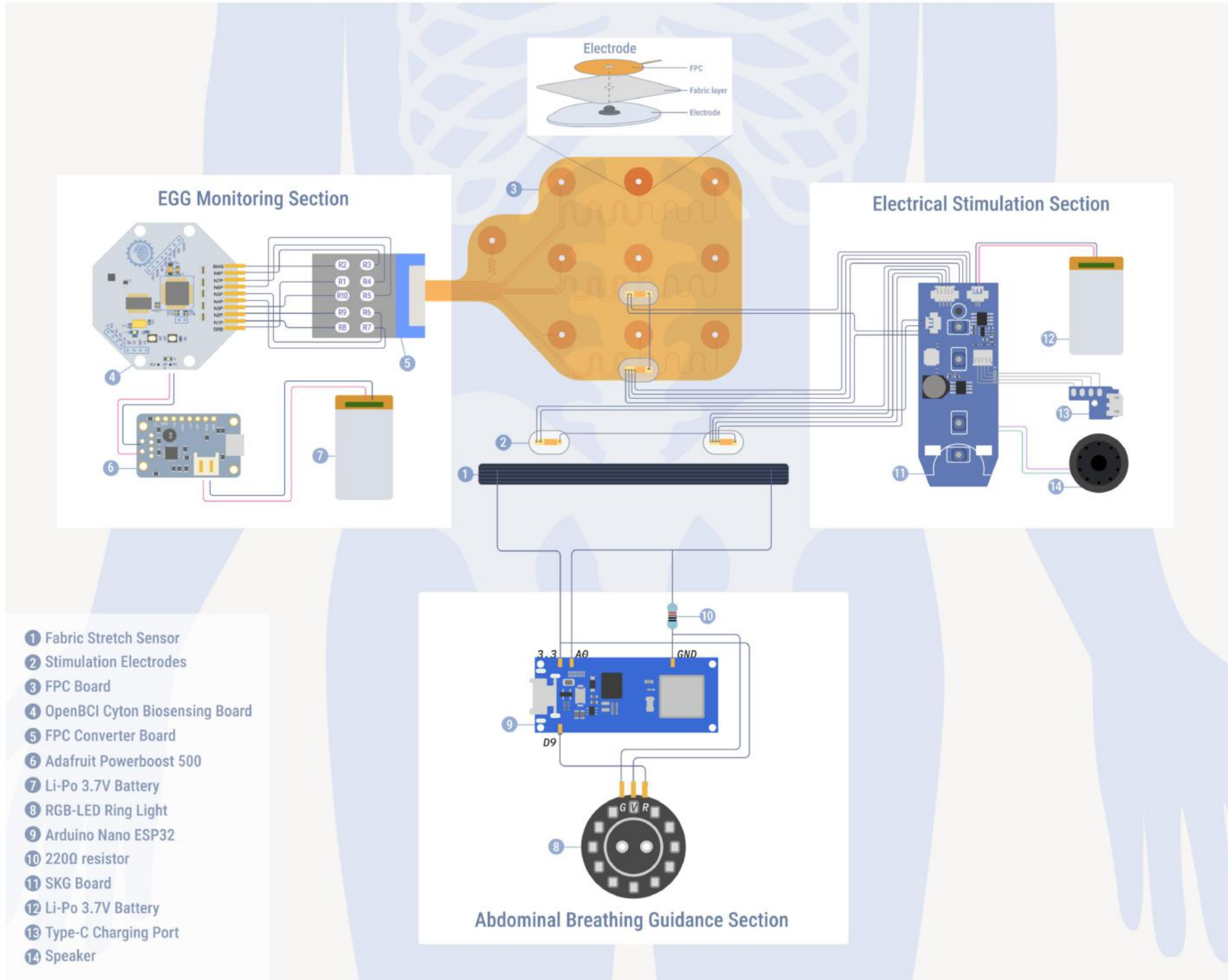

## User Flow

I developed **a comprehensive system that can monitor and regulate gastrointestinal disorders and the accompanying emotional problems,** with a mobile application that enables real-time control. For prediction, the system uses EGG to monitor gastrointestinal disorders and analyze potential emotional risk in real time. For regulation, it stabilizes emotional problems by guiding abdominal breathing and reduces gastrointestinal discomfort through electrical stimulation, enabling integrated care across both dimensions.




## Hardware Design

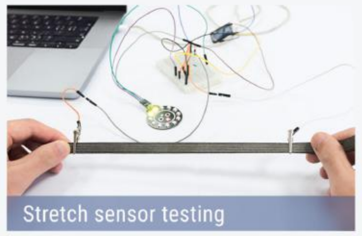
For the system's three core functions, I conducted tests on material and hardware selection and finalized the configuration: a flexible printed circuit (FPC) with Ag/AgCl ink + Cr/Au electrodes for signal acquisition, a fabric stretch sensor for breathing monitoring, and metal electrodes for electrical stimulation. Based on these components, I selected appropriate driver boards and completed the FPC design and circuit layout.



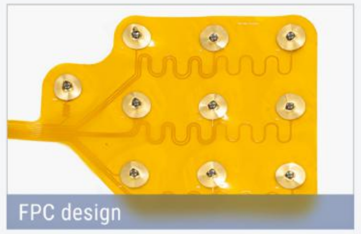
## ■ Prototyping

I tested and calibrated the performance of the EGG electrodes, electrical stimulation electrodes, and stretch sensors, and designed the FPC layout.


Electrical stimulation testing

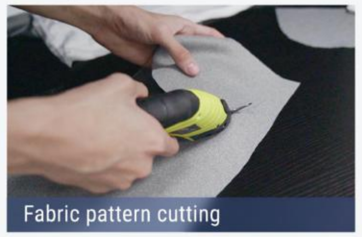

Stretch sensor testing


EGG sampling testing

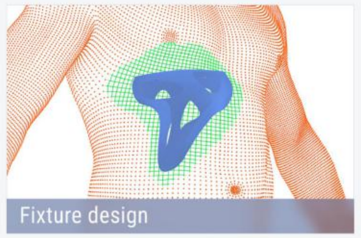

FPC design

I first built an initial prototype to evaluate functional reliability. I then optimized the hardware layout by designing an abdomen-conforming structure to ensure stable fixation of all components.

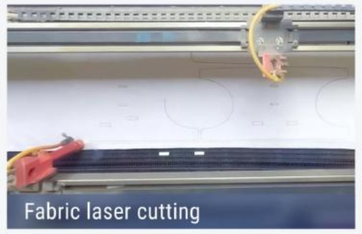

Hardware soldering


Fabric pattern cutting


Prototype 1.0 wearability test


Fixture design

I developed the second prototype with a focus on ergonomic design, selecting flexible fabrics that were laser-cut and sewn together with the hardware and skin-contact electrodes.

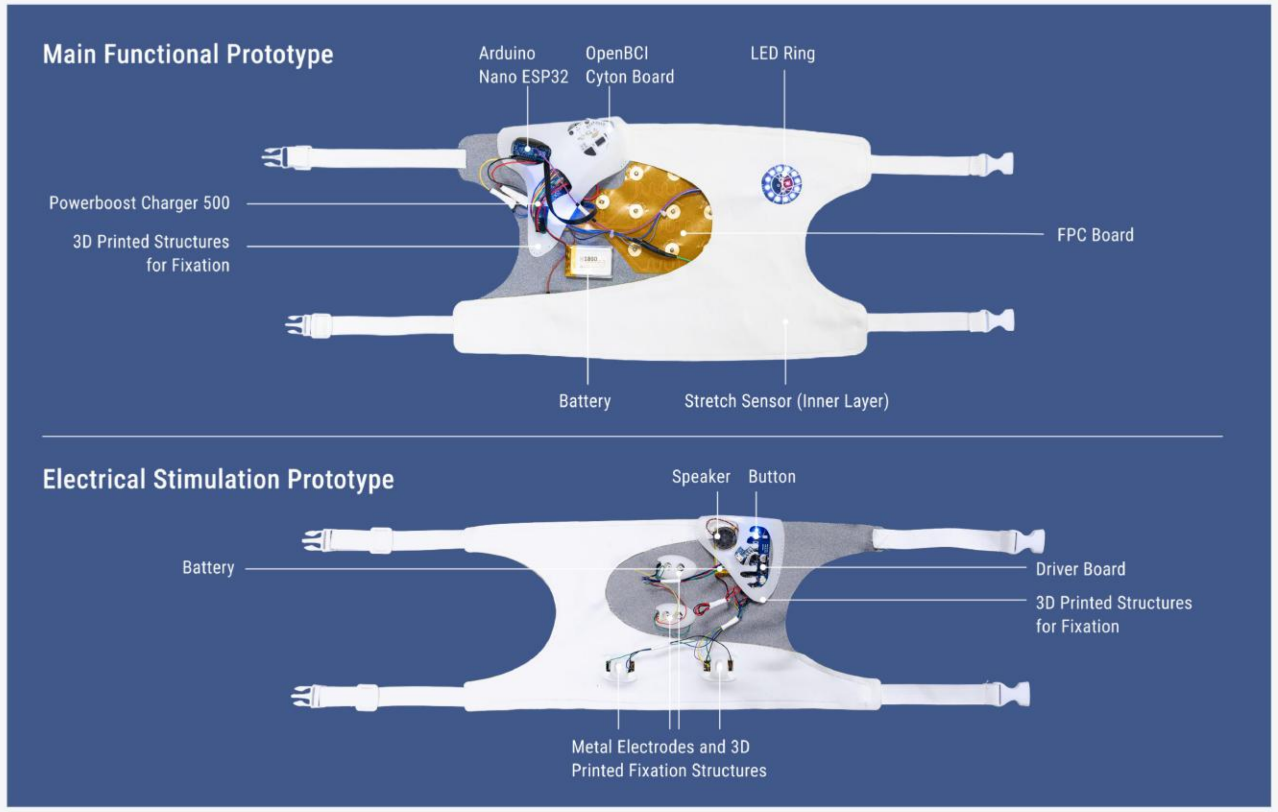

Fabric laser cutting


Component sewing


Electrode mounting

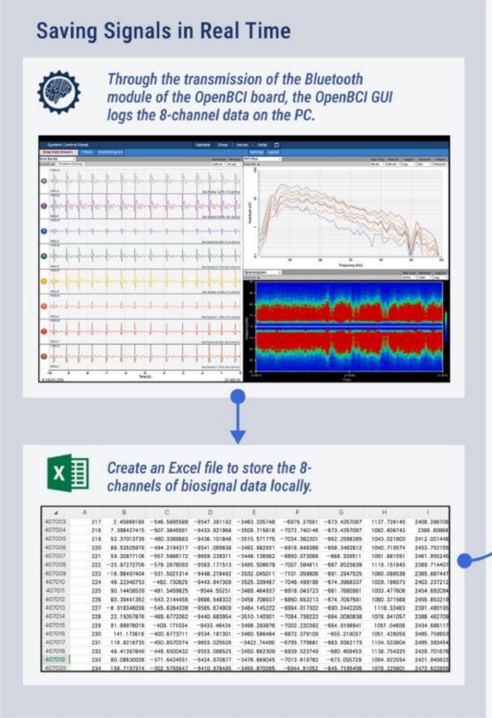

Prototype 2.0 wearability test

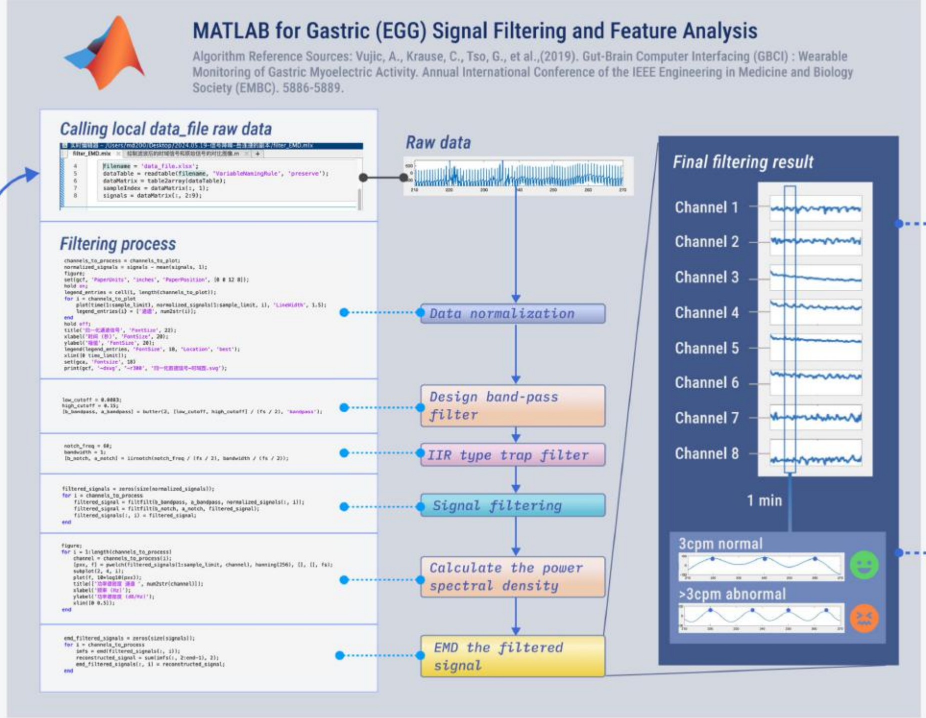
**Final Output:** I developed a wearable functional prototype, with the electrical stimulation module separated as an independent prototype to ease manufacturing and testing.

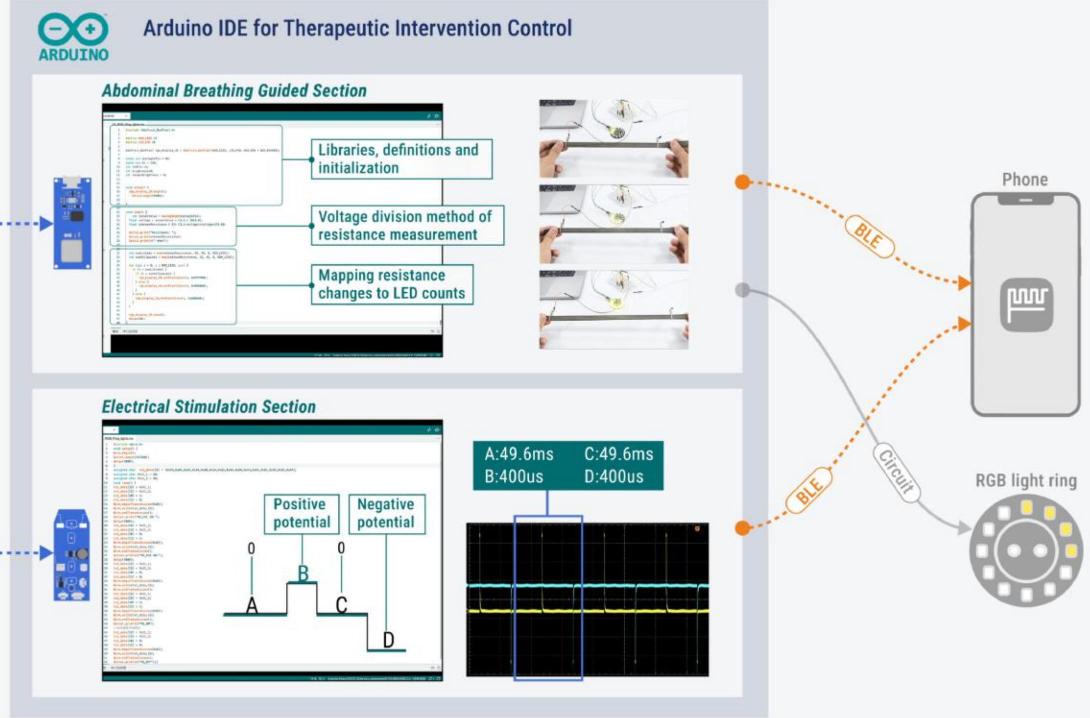



## ■ Coding

The raw data contained interference from respiration and heartbeat. Following methods from previous studies, I **filtered the signals in MATLAB** to extract the EGG waveform at approximately three cycles per minute (cpm), verified its normality, and transmitted the data to a smartphone in real time. When abnormalities were detected, a program was executed **through the Arduino IDE** to activate the two regulation modules. The data were then sent via Bluetooth to the smartphone's graphical user interface (GUI).

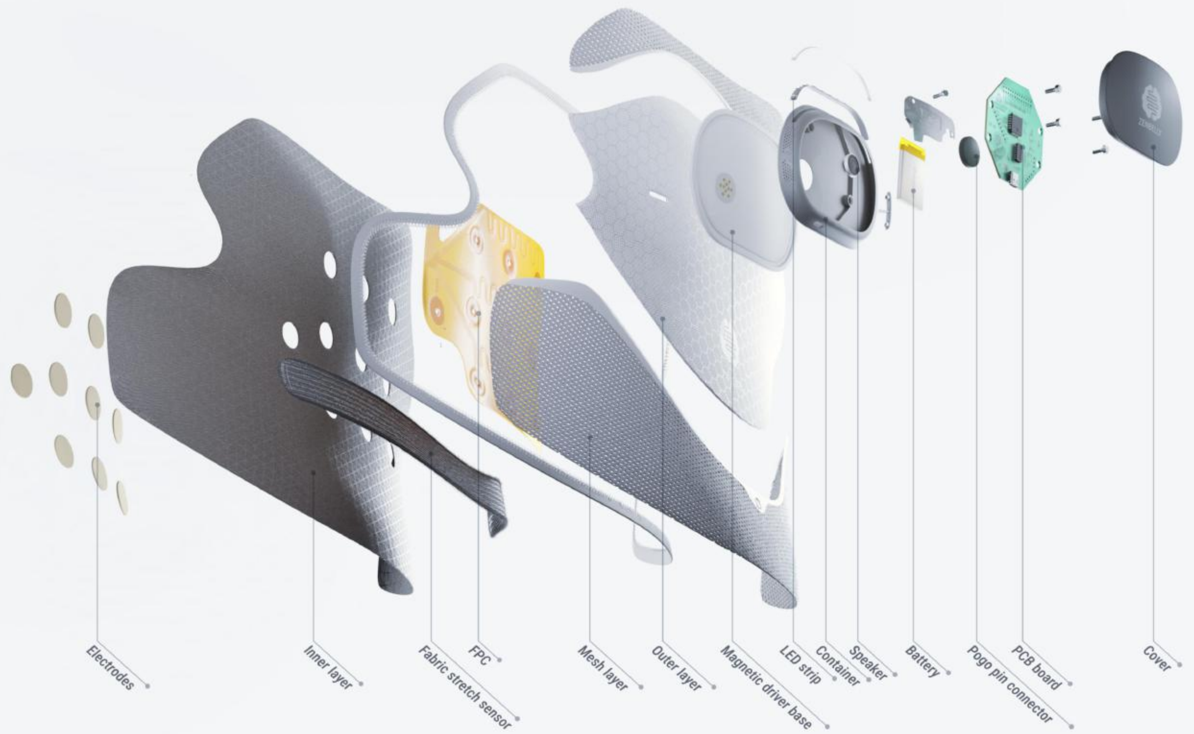


## Product Design

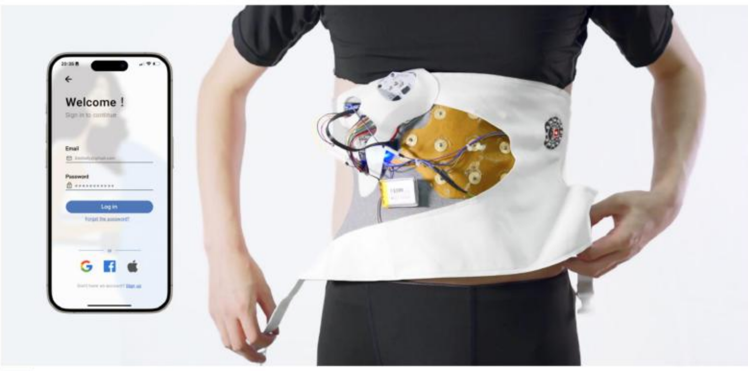
ZenBelly is a wearable device designed for gut-brain health management, suitable for long-term use both indoors and outdoors. It features a magnetic, detachable driver module that supports continuous use and easy cleaning.





## Workflow

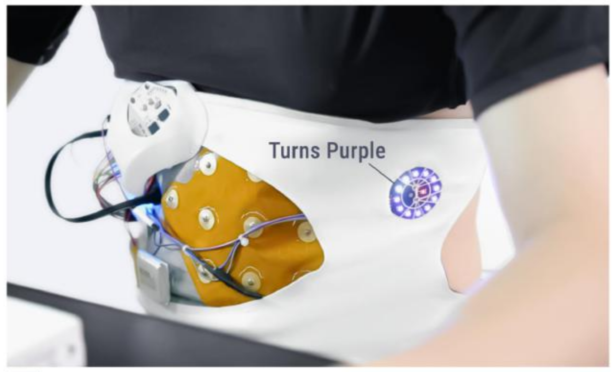
Paired with the ZenBelly app, users can connect the device, monitor signals, adjust therapeutic settings, and track daily health data. This system enables comprehensive management of gut-brain conditions anytime, anywhere.




1 Wearing and Activating the Device

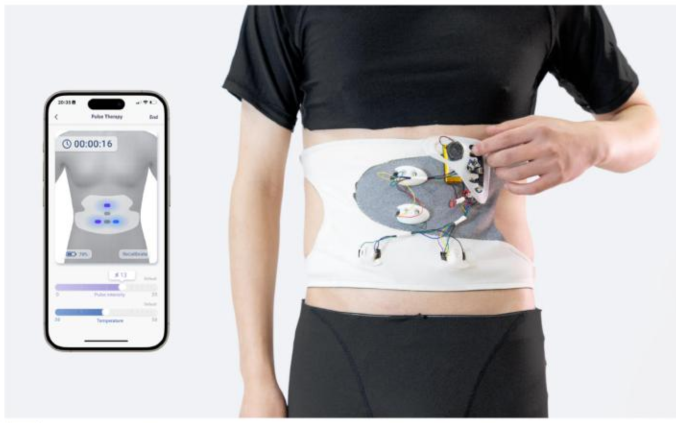
2 Connecting the Device via Bluetooth

3 Detecting EGG Signals and Analyzing Emotional Risk

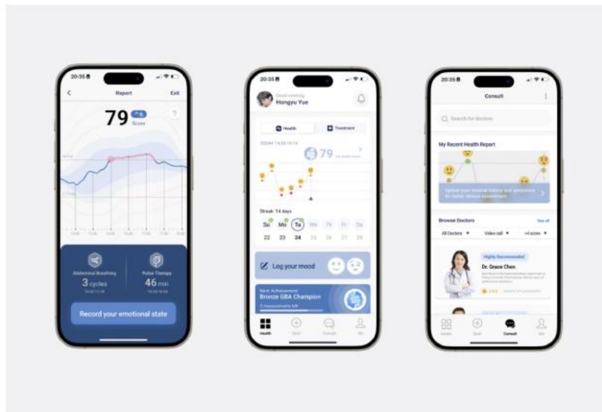



4 Abnormality Detected

5 Guiding Abdominal Breathing for Emotional Regulation



6 Applying Electrical Stimulation for Gut Regulation



7 Daily Health Management

Four-Person Collaborative Project

**Contribution**
**Project Lead**
Concept Development; Visual Design; App Development

**Collaborator**
Fengyu Wang, Xinyue Zhang, Zhaoyang Zhong

**Keywords**
Speculative Design; Printed Media; App

**Instructor**
Prof. Qin Du

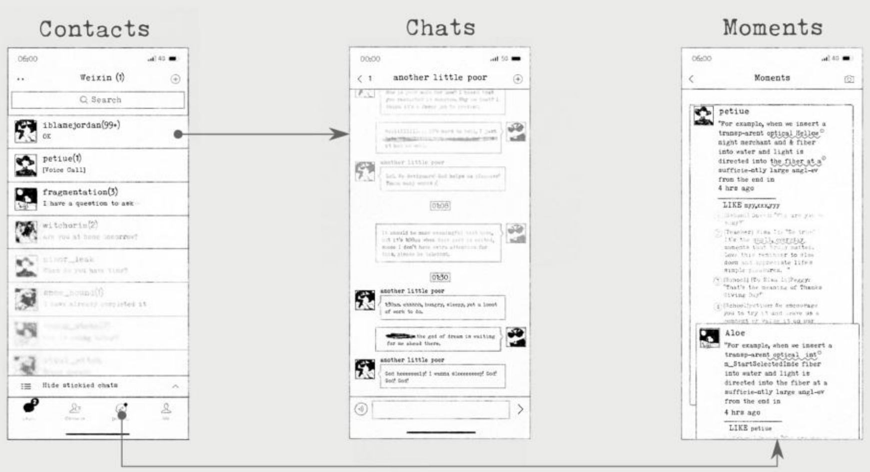
06

# Paper WeChat

Reimagining Social Media Through the Logic of Printed Media

In an era where digital information continues to accelerate, the warmth and texture once unique to printed media are gradually fading from daily life.

Paper WeChat reimagines WeChat's interaction model through the logic of printed media: text gradually blurs over time or "wrinkles" with repeated reading, the "Moments" are transformed into a layered, browsable newspaper... The project leverages the metaphor of paper to provoke reflection on old tangible media.




First Prize
Hong Kong Digital Arts Design Competition
2024

First Prize
Orient Design Award
2024

March 2024 - April 2024
Tongji University, Shanghai, China

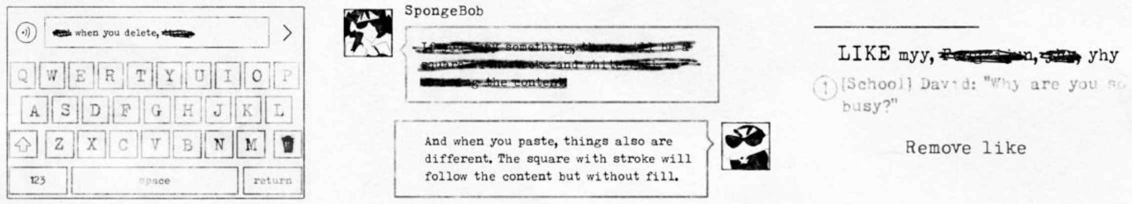
https://youtu.be/UOZR0faol8M

## Redesigning Interactions

**[1] Text copying through "tearing":** Long-pressing and sliding to select text; the chosen words are torn off and pasted into the input box, leaving the original spot emptied, mirroring how printed text can only be cut and reassembled, not duplicated.

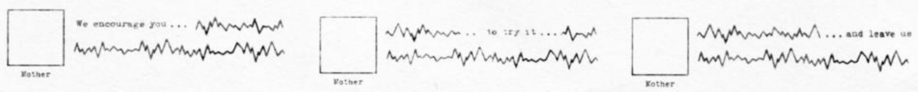
Open the input box — Copy and paste — Send

**[2] Text deletion through scribbling:** Tapping the delete icon scribbles over the text, and the scribble marks remain visible after the message is sent; long pressing and swiping to recall a message scribbles out the entire text. This preserves the irreversibility of text editing on paper.



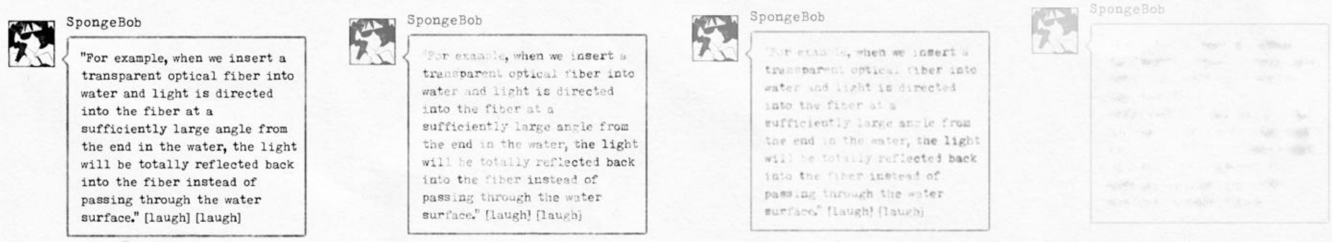
Delete text — Recall message — Remove like

**[3] Fragmentary speech-to-text:** Tapping the voice bubble plays the audio and converts it into text, but only isolated words are displayed, resembling the broken continuity of old telegrams.



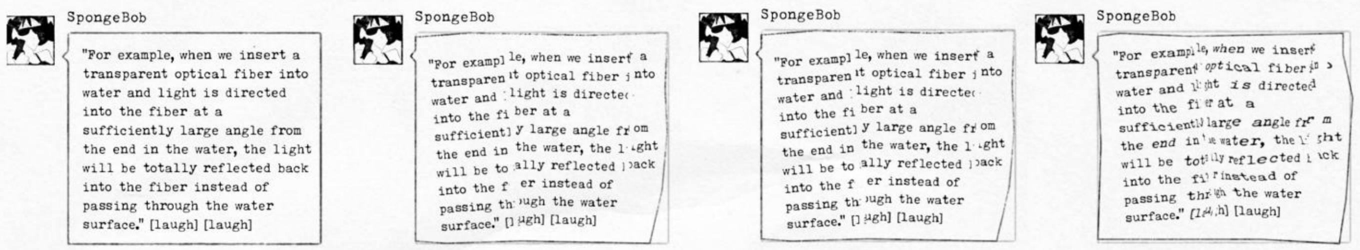
Speech-to-text

**[4] Information fades over time:** Historical messages gradually blur, echoing the way printed materials wear and fade with age.



10 min — 20 min — 30 min — 50 min

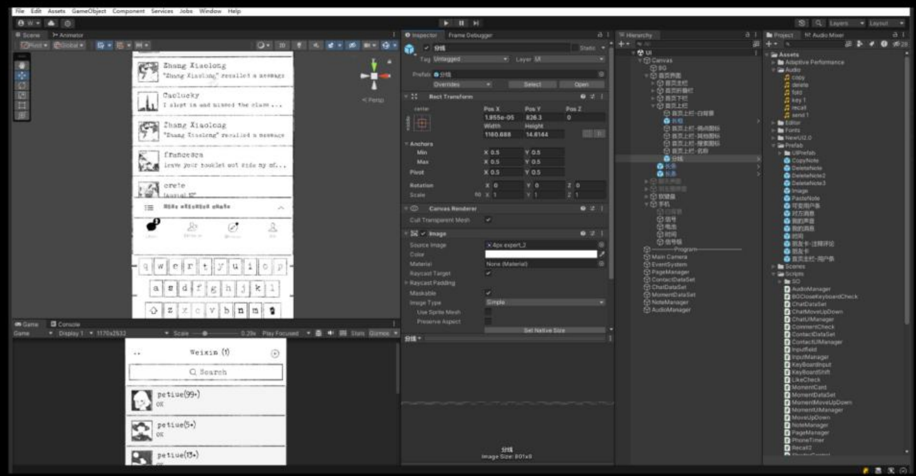
**[5] Chat bubbles crease with repeated reading:** Tapping a message multiple times causes the bubble to wrinkle, like paper thumbed through again and again.

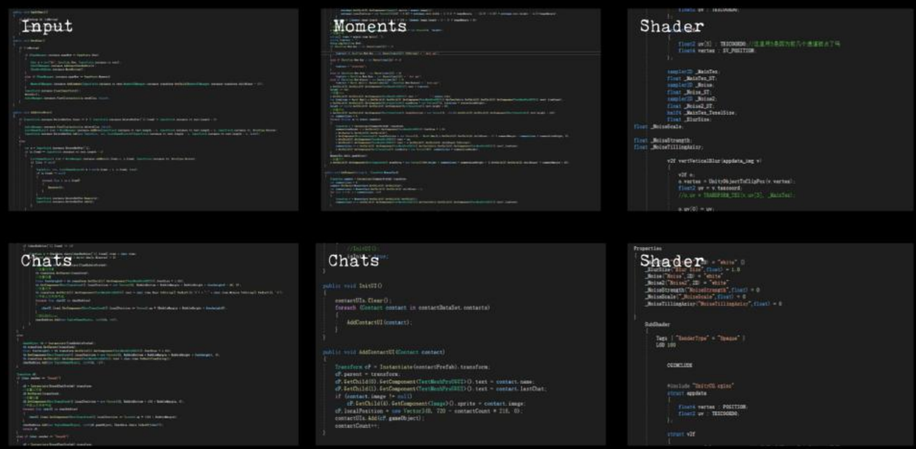


1 time — 5 times — 10 times — 15 times

## Development

Using Unity, we developed a standalone mobile application called Paper WeChat.





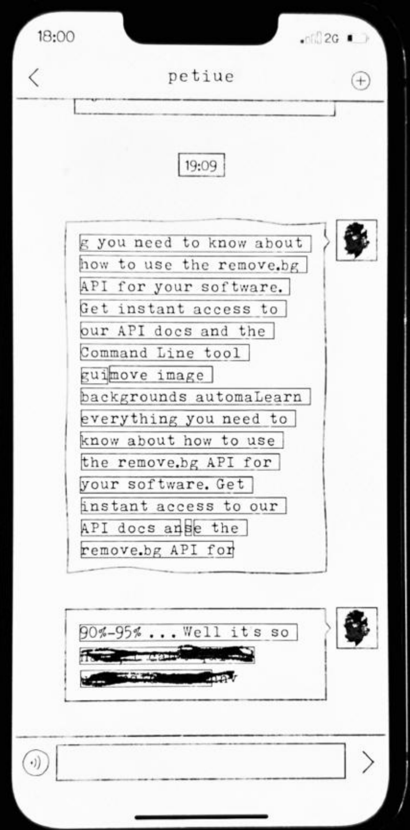

## Exhibition

## Interface Demonstration

We built an iOS-compatible version; shown here is a live demo running on an iPhone 12.

Moments Page


Chat Page




## Capstone Project

**Keywords**
Smart Textiles, Rehabilitation,
Deep Learning, Wearable Device

**Instructor**
Prof. Qi Wang, Director of CDI lab, Tongji University

**Status**
Ongoing

07

# X-Garment

### A Smart Garment for Muscle Compensation Recognition

Compensation is the unconscious use of other muscle groups functionally replace fatigued or injured muscles. Although such compensatory strategies may temporarily enable task completion, persistent reliance on them can lead to secondary injuries, thereby complicating rehabilitation and injury prevention.

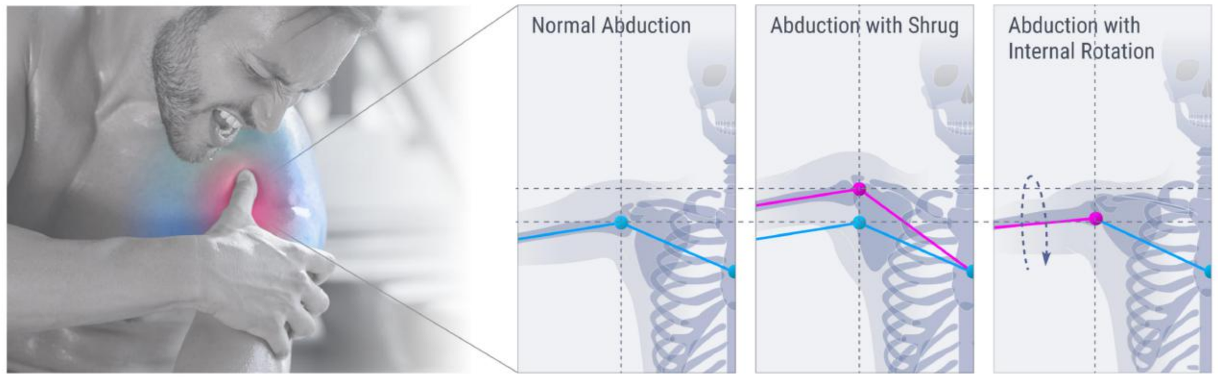
This project presents a fully textile-integrated wearable system combined with neural networks to detect compensatory movements, estimate joint angles, and provide real-time feedback, supporting effective home-based rehabilitation training.

*September 2025 – Present*
*Tongji University, Shanghai, China*

## ■ Problem & Project Direction

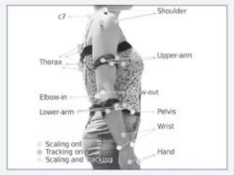
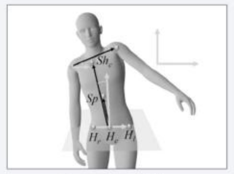
**Compensation** is the unconscious use of other muscle groups to assist or substitute for fatigued or impaired muscles during a movement. Although the motion may appear nearly correct, the joint is loaded improperly, reducing the effectiveness of rehabilitation and increasing the risk of secondary injuries. These compensations are hard to detect in traditional training and even more difficult to correct once they become habitual.

This led me to ask: **Could a lightweight garment, similar to a regular sports top, continuously detect muscle compensatory patterns in real time?** This would facilitate effective home-based rehabilitation training.



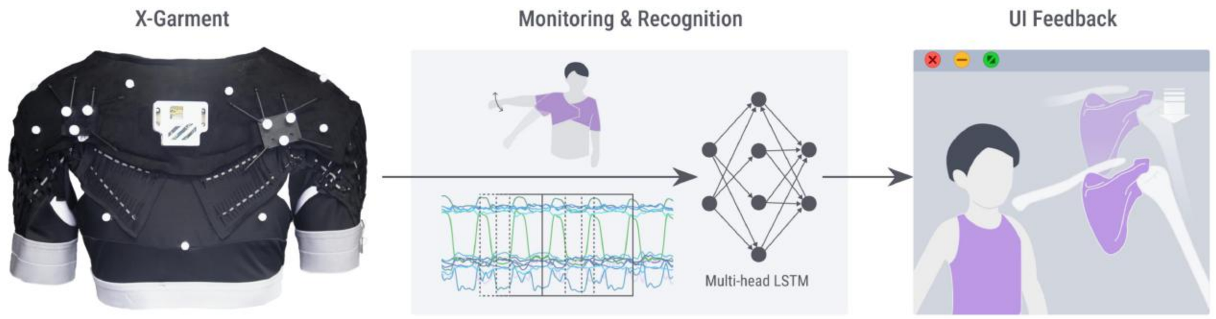

## ■ Gaps in Existing Research

Current compensation monitoring relies heavily on optical motion capture, cameras, or IMU sensors. These approaches are **costly, prone to occlusion or drift, and challenging to deploy** in home-based rehabilitation scenarios. A fully textile-based monitoring garment offers far greater potential for daily use. However, accurately recognizing subtle compensatory patterns in multi-DoF movements using soft textile structures **remains a significant technical challenge**.

| Non-Wearable Devices | | Wearable Devices | |
|---|---|---|---|
|  Optical Motion Capture |  Computer Vision |  EMG |  IMUs |
| High accuracy | Easy to access | Directly reflects muscle activity | Simple to use with high accuracy |
| Complex and expensive | Low accuracy | Uncomfortable and difficult to reuse | Uncomfortable with poor long-term stability |

## ■ Approach

My approach embeds **textile stretch sensors** within the garment, enabling them to **deform with body movement** and produce continuous strain signals. Combined with **deep learning models**, the system identifies subtle compensatory patterns and estimates joint angles. This architecture offers clear advantages in wearability, comfort, and data richness.

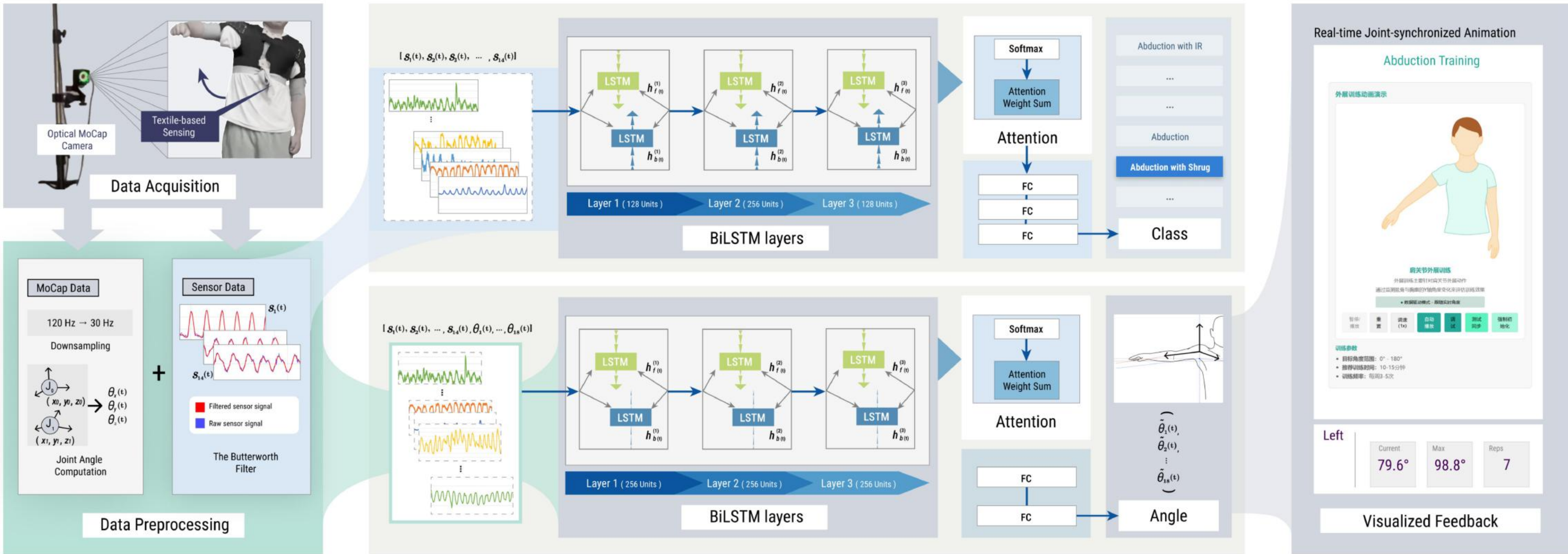


## ■ System Design

The system uses a one-time optical motion capture session solely for initial calibration to establish ground-truth joint angles. During actual training, stretch sensors deform passively with movement, converting strain into electrical signals.

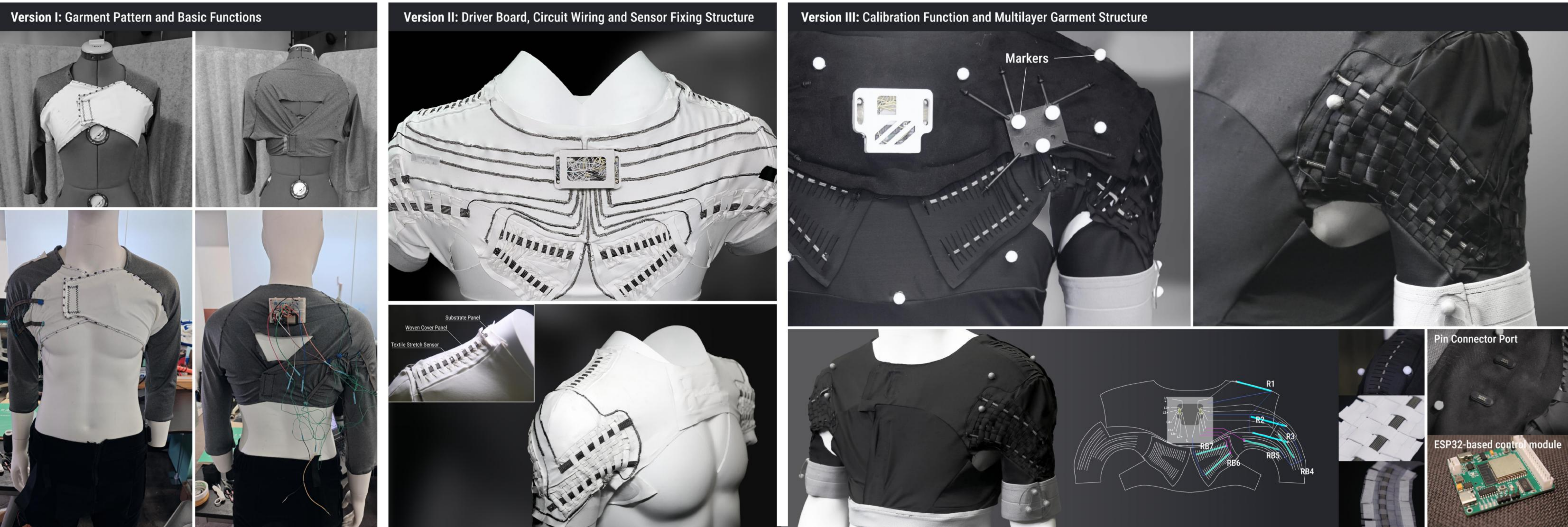
The analysis framework contains **two parallel processing paths:**
1. Compensation Recognition Path: A BiLSTM with an attention mechanism processes the 14-channel sensor sequences to classify movement patterns and determine whether the current repetition is performed correctly.
2. Angle Regression Path: An Attention-LSTM maps the same time window into Euler angles, quantifying how much each joint actually rotates.

Together, these two paths drive a real-time interface that displays both whether compensation occurs and the precise joint angles.




## ■ Smart Garment Design

To obtain stable and reliable sensing data, the stretch sensors and conductive fibers must be **securely integrated** into the fabric while remaining **free from unwanted stretching or mechanical interference**. This imposes strict requirements on garment structural design. I therefore performed multiple iterations and optimizations across garment patterning and routing, sensor placement and fixation, and integration of the driver module.

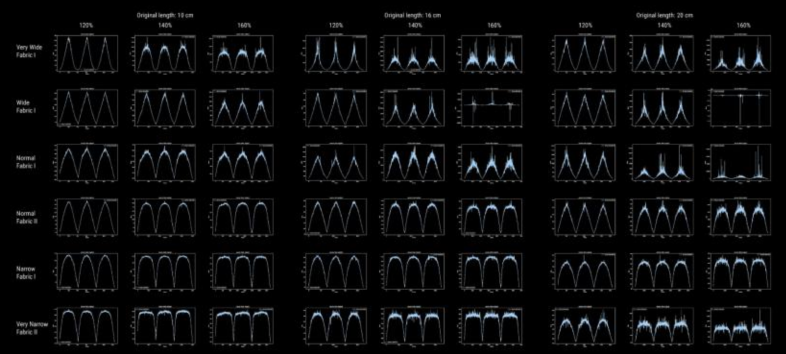


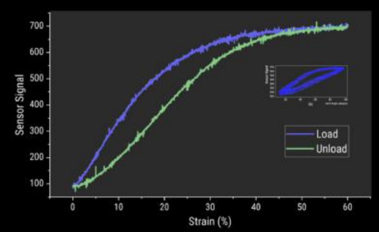
## Ongoing Work

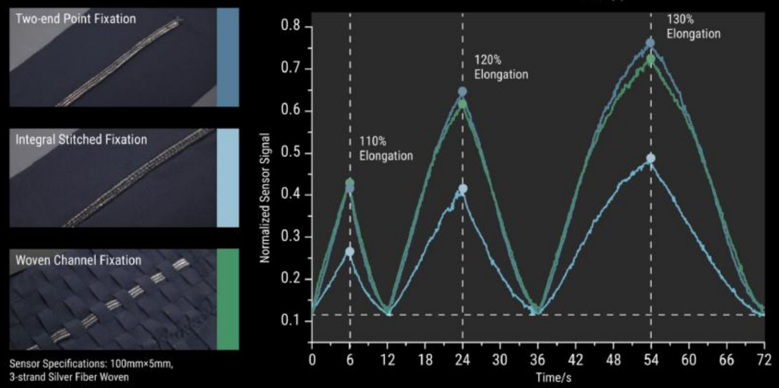
Repeated donning and doffing, along with extended movement, cause relative displacement between garment and skin. Additionally, the generic sensor layout still leaves room for improved information efficiency. My next phase will focus on systematically **refining sensor structure, layout, and garment architecture** to enhance signal reliability during **prolonged use.**

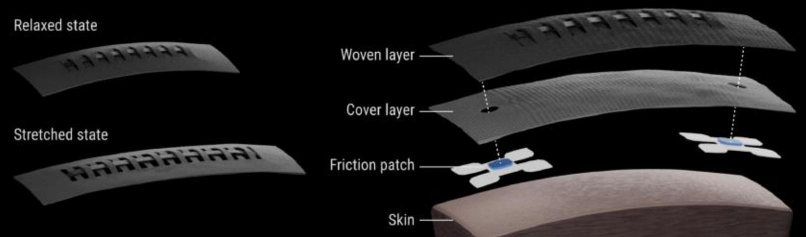
### Sensor Selection and Fixation

I conducted a systematic analysis of sensor length, width, material properties and fixation strategies. Ultimately, I adopted a Directional Scales Weave, paired with friction-enhancing patches that contact the skin, enabling the sensors to maintain a stable relative position



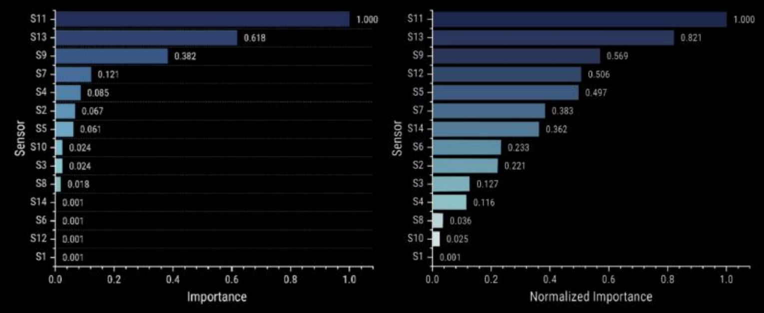



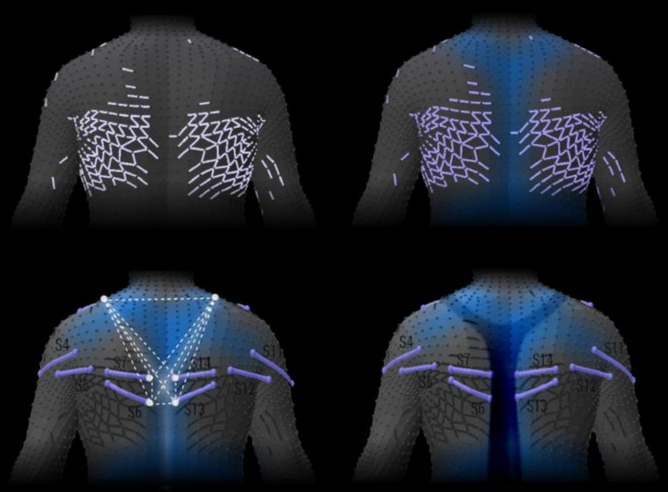



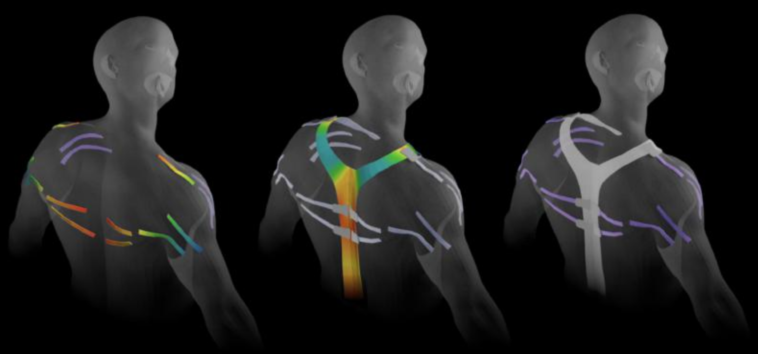




### Sensor Layout and Structural Stabilization Design

I used key rehabilitation movements to capture surface point-cloud data and identify high-deformation regions on the skin. Sensors were placed in these regions and validated using Permutation Importance. I also created a TPU rigid structure based on spinal deformation patterns and anchored one end of the back sensors to it, helping maintain stability during large movements.



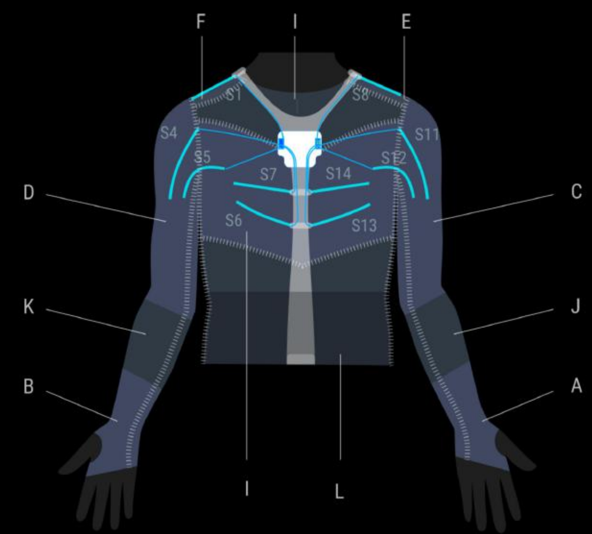


### Garment Design

I redesigned the garment according to the updated sensor layout: non-sensing regions use more supportive materials to maintain stability, while sensor-integrated regions preserve elasticity to avoid interfering with strain measurement.

A-I Stretchable textile J-N: Rigid textile

Back View




Front View