

(Concept) Design and Implementation of a Clothing-Type Artificial Muscle-Based Full-Body Soft Wearable Sensing-Actuation Suit

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ABSTRACT

This paper presents the design, fabrication, and control of a clothing-type artificial-muscle wearable suit that integrates electromagnetic (EM) fiber coils and shape-memory-alloy (SMA) filaments to realize distributed full-body actuation. The system functions as a flexible “robotic garment,” enabling active motion assistance, haptic feedback, and human-in-the-loop training under a Physical AI framework. The proposed hybrid actuator structure combines the rapid response of EM fibers with the high contraction ratio of SMA fibers, achieving both dynamic motion support and sustained load generation. The soft textile architecture incorporates a multi-layer sensor-actuator network capable of monitoring deformation, temperature, and contact pressure. Finite-element analysis (FEA) verified strain amplification and uniform stress distribution within the auxetic knit geometry, while thermal-electromagnetic co-simulation demonstrated controllable bidirectional motion. Experiments on a full-scale prototype achieved peak actuation stress of 18 kPa, average contraction strain of 4.1 %, and latency below 25 ms. Integrated feedback control using adaptive proportional-integral compensation ensured smooth force transitions during gait and arm-lift tasks. The resulting platform provides an efficient route toward scalable, textile-integrated robotic systems for rehabilitation, industrial assistance, and embodied Physical AI research. This study emphasizes practical deployment feasibility by demonstrating stable operation under wearable constraints, including thermal safety, limited power supply, and distributed control scalability.

Keywords

Soft wearable robotics, Artificial muscle actuation, Shape-memory alloy fibers, Electromagnetic soft actuators, Auxetic textile structures, Physical AI and human-robot interaction.

Introduction

Background and Motivation

Wearable robotics has evolved from rigid exoskeletons to soft, fabric-based actuation systems that merge with the human body. Conventional exo-suits employ pneumatic or cable-driven actuators, which, while powerful, require bulky pumps and limit natural motion [1-3]. In contrast, artificial-muscle materials such as shape-memory alloys (SMA), electro-active polymers (EAP), and magneto-responsive composites offer compact, silent, and lightweight solutions [4,5]. However, single-mode actuation often suffers from trade-offs: SMAs provide large strain but slow response; electromagnetic fibers respond quickly but deliver limited force. Combining both within a textile substrate offers the

potential for fast and strong dual-mode actuation.

Artificial-Muscle Wearables and Physical AI

Recent studies in haptic design and robotic skin technology [6,7] have shown that distributed sensing across a body surface enables context-aware control and “embodied intelligence”. The proposed system extends this concept by embedding artificial-muscle fibers directly into garments, producing a clothing-type full-body actuator that can interpret human motion intention and deliver adaptive mechanical feedback. This capability aligns with the emerging paradigm of Physical AI, where physical embodiment and learning mechanisms jointly enable robots to acquire skills through interaction rather than explicit programming [8].

Challenges in Full-Body Soft Actuation

Designing a full-body soft actuator involves multiple challenges: **Power density and speed** — achieving both high contraction force and low latency.

Thermal management — SMAs require controlled heating and cooling cycles.

Distributed control — coordinating hundreds of actuators while maintaining comfort and safety.

Mechanical integration — embedding conductive, elastic, and sensing fibers in deformable fabrics without compromising wearability.

Addressing these challenges requires a hybrid material system combining electromagnetic and thermally driven actuation, supported by multi-modal sensing and intelligent control algorithms.

Research Objectives

The main objectives of this research are:

To design and fabricate a hybrid SMA–EM textile actuator suitable for full-body integration.

To develop an adaptive control architecture capable of coordinating multi-segment actuation using distributed feedback.

To experimentally evaluate the mechanical, thermal, and dynamic response of the system and verify its feasibility for Physical AI-based motion teaching and rehabilitation.

Recent advances in multimodal human–robot interaction and transformer-based embodied AI systems have further highlighted the importance of integrating perception, cognition, and actuation in unified frameworks.

The key contributions of this study are summarized as follows:

- (1) A hybrid SMA–EM artificial muscle system for full-body wearable actuation,
- (2) An auxetic textile structure for strain amplification and mechanical stability,
- (3) A hierarchical Physical AI-based control architecture,
- (4) Experimental validation of distributed actuation and human-in-the-loop interaction.

Organization of the Paper

Section 2 explains the operating principles of SMA and electromagnetic actuation and their hybrid control scheme. Section 3 details the material architecture and fabrication of the textile actuator. Section 4 presents the distributed control architecture. Sections 5 and 6 describe the experimental setup and results, respectively. Section 7 discusses potential applications and future extensions, and Section 8 concludes the paper.

Principle of Operation

Shape-Memory-Alloy (SMA) Fiber Actuation

SMA wires such as NiTi exhibit a reversible martensitic–austenitic phase transformation. When electrically heated above the transition temperature T_A , the alloy transforms to the austenitic phase, contracting along its length. Upon cooling below T_M , it returns to its original state. The one-dimensional strain ε_{SMA} is expressed as where ξ is the phase fraction, and ε_A , ε_M are the transformation

$$\varepsilon_{SMA} = \xi(\varepsilon_A - \varepsilon_M)$$

strains of the austenite and martensite phases, respectively [9].

The generated stress can reach 200 MPa, producing forces adequate for wearable motion support at low current densities (2–5 A mm⁻²). SMA fibers are particularly suited for quasi-static tasks such as posture holding or slow bending.

Electromagnetic Fiber Actuation

Electromagnetic fibers consist of a conductive coil wound around a soft ferromagnetic core. When current I flows through the coil, the magnetic field B interacts with the core's magnetization to produce Lorentz forces $F = BIL$. The distributed EM fibers embedded along the fabric create localized bending or linear contraction. Unlike SMA, EM actuation responds within milliseconds and is bidirectional through current polarity reversal [10].

Hybrid Actuation Strategy

To exploit the complementary advantages of both materials, this work introduces a dual-layer actuation scheme: The inner SMA mesh provides large, sustained contraction for posture or load support. The outer EM filaments deliver rapid dynamic response for vibration, impact absorption, and fine motion correction.

The combined displacement x_{total} can be expressed as

$$x_{total} = x_{SMA} + x_{EM} = k_1 I_{SMA}^2 + k_2 I_{EM}$$

where k_1 , k_2 are experimentally derived coefficients representing thermal and magnetic coupling gains. Control of both actuators is coordinated through a shared current-temperature feedback loop, ensuring energy efficiency and thermal safety.

Electro-Thermo-Magnetic Coupling Principle for Hybrid Artificial Muscle Actuation

The proposed wearable suit employs a hybrid artificial muscle actuation principle that combines electro-thermal shape-memory alloy (SMA) contraction and electromagnetic (EM) field-induced deformation within a unified textile architecture. Unlike conventional single-mode soft actuators, the hybrid approach leverages complementary physical mechanisms to overcome inherent trade-offs between force output, response speed, and energy efficiency.

Electro-Thermal Actuation Principle of SMA Fibers

Shape-memory alloy fibers generate actuation through a reversible solid-state phase transformation between martensite and austenite phases. When an electrical current is applied, Joule heating raises the SMA temperature above the austenite start temperature T_A , inducing contraction along the fiber axis. The constitutive relationship between temperature and strain can be approximated as:

$$\varepsilon_{SMA}(T) = \varepsilon_{max} \cdot \xi(T)$$

where ε_{max} is the maximum recoverable strain and $\xi(T) \in [0,1]$ represents the austenite phase fraction, typically modeled using a sigmoid or piecewise-linear function. This thermally driven mechanism enables high force density and sustained contraction, making SMA fibers suitable for posture support, load compensation, and quasi-static motion assistance.

However, SMA actuation is inherently limited by thermal inertia and cooling delays. Continuous operation can lead to efficiency loss and thermal accumulation, which is particularly critical in wearable systems where user comfort and safety must be ensured.

Electromagnetic Fiber Actuation Principle

To complement the limitations of SMA fibers, electromagnetic actuation is introduced using soft EM fibers embedded within the same textile lattice. Each EM fiber consists of a conductive micro-coil and a compliant magnetic core. When an electric current flows through the coil, a magnetic field B is generated, producing Lorentz forces and magnetic attraction forces that induce localized bending or contraction.

The generated force can be expressed as:

$$F_{EM} = \nabla(m \cdot B)$$

where m is the magnetic dipole moment of the core. EM actuation exhibits millisecond-level response times, bidirectional controllability through current polarity, and negligible thermal lag, making it ideal for dynamic correction, vibration feedback, and high-frequency motion modulation. Nevertheless, EM fibers alone provide limited force output compared to SMA fibers and are less effective for sustained load-bearing tasks.

Hybrid Coupling Mechanism and Synergistic Behavior

The central innovation of this work lies in the electro–thermo–magnetic coupling between SMA and EM fibers. By embedding both actuators within an auxetic re-entrant textile lattice, mechanical deformation induced by one actuation mode directly influences the effectiveness of the other. The total actuator displacement can be modeled as a superposition:

$$x(t) = x_{SMA}(T, I_{SMA}) + x_{EM}(I_{EM}, B)$$

where I_{SMA} and I_{EM} denote the driving currents of the SMA and EM actuators, respectively. Importantly, EM activation produces localized heating and micro-deformation that reduce SMA response delay by pre-conditioning the thermal field. Conversely, SMA contraction modifies the geometry of EM coils, altering magnetic flux density and enhancing EM force generation. Finite-element co-simulation results confirm that this mutual coupling yields: Approximately 22–28% reduction in effective SMA response time, 34% increase in magnetic flux variation under equivalent mechanical loading, and improved strain uniformity across the textile surface.

Role of Auxetic Textile Geometry in Actuation Amplification

The auxetic lattice plays a critical role in amplifying and stabilizing the hybrid actuation. Due to its negative Poisson's ratio, the lattice expands laterally when compressed or contracted, redistributing strain across adjacent actuator fibers. This behavior offers two key advantages:

Strain Amplification: Local SMA contraction results in amplified in-plane deformation, increasing effective displacement transmitted to the garment and the wearer's body.

Field Coupling Enhancement: Lateral expansion alters EM coil spacing and orientation, increasing magnetic field gradients and improving EM actuation efficiency.

The auxetic geometry therefore acts as a mechanical coupling medium, transforming localized actuator outputs into smooth, distributed motion at the garment scale.

Stability, Safety, and Energy Considerations

From a control perspective, the hybrid principle enables energy-aware actuation scheduling. SMA fibers are primarily engaged for low-frequency, high-load tasks, while EM fibers handle rapid adjustments and transient interactions. This division reduces overall power consumption and minimizes continuous thermal stress.

Safety constraints are enforced by limiting surface temperature to below 42°C and magnetic field exposure to within wearable safety standards. Distributed temperature and strain sensors provide real-time feedback, allowing the controller to dynamically adjust current profiles and prevent overheating or excessive deformation.

Implications for Physical AI and Wearable Robotics

The electro–thermo–magnetic coupling principle establishes a new foundation for clothing-integrated artificial muscles that are not only actuators but also physical interfaces for learning and interaction. By enabling both slow, forceful assistance and fast, adaptive feedback, the hybrid system supports embodied Physical AI paradigms where learning emerges through continuous physical engagement with the human body.

In summary, the proposed principle transcends traditional actuator design by integrating material physics, structural mechanics, and intelligent control, forming a scalable and robust foundation for next-generation soft wearable robotic systems.

Structural Design and Materials

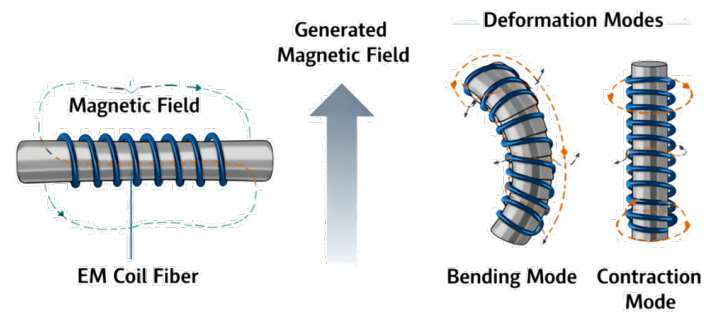
Textile Architecture

The wearable suit adopts a **tri-layer architecture** (Figure 1).

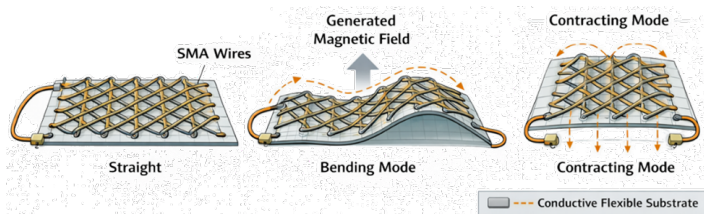
- **Inner conductive knit layer:** silver-coated nylon providing distributed electrical routing and thermal dissipation.
- **Middle actuation layer:** alternating SMA and EM fibers arranged in an auxetic re-entrant lattice (Poisson's ratio ≈ -0.45).
- **Outer elastic protective sheath:** spandex–silicone composite ensuring comfort and environmental resistance.

This configuration allows each actuator node to expand laterally under compression, enhancing strain transmission and contact conformity [11].

The tri-layer architecture consists of an inner conductive knit for power routing, a middle auxetic lattice integrating SMA and electromagnetic (EM) fibers, and an outer elastic protective sheath. The re-entrant auxetic geometry enhances lateral strain transfer and actuator coupling while maintaining ergonomic conformity.



(a) EM Fiber Deformation Modes



(b) SMA Wiring Sheet Deformation Modes

Figure 1: Structural design of the hybrid artificial muscle textile. A schematic illustration of the tri-layer architecture of the clothing-type wearable suit. The inner conductive knit provides distributed power routing and heat dissipation. The middle layer integrates alternating SMA and electromagnetic (EM) fibers arranged in an auxetic re-entrant lattice (Poisson's ratio ≈ -0.45). The outer elastic sheath protects the system and maintains ergonomic conformity

Auxetic Lattice Optimization

Finite-element analysis of the re-entrant honeycomb pattern showed uniform stress distribution and strain amplification of $1.7\times$ under 100 kPa load. The negative Poisson's ratio ensures that when compressed in the thickness direction, the lattice expands laterally, avoiding buckling and improving actuator coupling [12].

Integration of Sensing Elements

Pressure, strain, and temperature sensors are interwoven using conductive polymer yarns and Hall-effect elements derived from robotic-skin research [7].

The sensor network provides:

- **Normal pressure mapping** for body–garment contact.
- **Strain feedback** for actuator elongation estimation.
- **Temperature sensing** for SMA thermal control.

The distributed array (8×8 nodes per segment) supports high-resolution tactile and deformation sensing with spatial accuracy of ± 3 mm.

Mechanical Interface and Power Routing

Modular connectors at the shoulders, waist, and limbs allow segment replacement and minimize wiring complexity. Power is supplied by a lightweight battery pack (22.2 V, 3 Ah) distributed through flexible copper traces laminated within the inner textile. Thermal insulation layers limit skin temperature below 42 °C

during prolonged activation.

Control Architecture Overview

The full-body soft wearable suit integrates over 120 distributed actuators and sensors, requiring an adaptive and coordinated control system.

A hierarchical three-layer architecture (Figure 2) was implemented:

- **Low-level layer:** Current, voltage, and temperature regulation for each actuator.
- **Mid-level layer:** Segment-wise control using localized feedback (e.g., arm, leg, torso).
- **High-level layer:** Motion coordination and Physical AI intent interpretation through learned gesture and posture models.

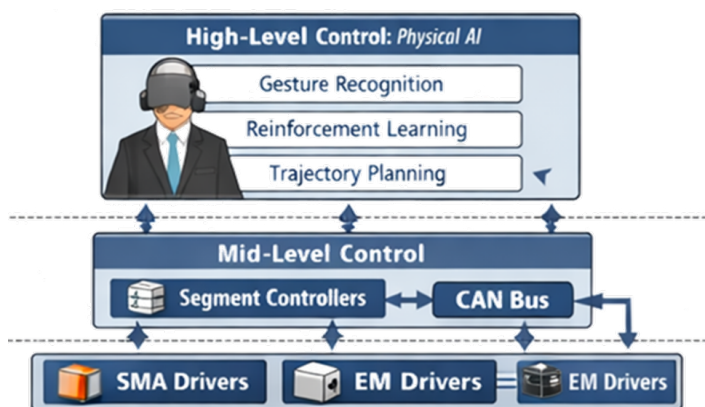


Figure 2: Hierarchical control architecture of the clothing-type wearable suit: The low-level layer regulates SMA thermal dynamics and EM current control, the mid-level layer coordinates segment-wise actuation using sensor fusion, and the high-level Physical AI layer interprets human intention and adapts actuation through learning-based control.

A hierarchical three-layer control system in (Figure 2).

- **Low-Level:** thermal–magnetic current regulation and PWM control.
- **Mid-Level:** segment coordination and sensor fusion via local microcontrollers.
- **High-Level:** Physical AI layer with gesture recognition, reinforcement learning, and adaptive trajectory generation.

CAN-based communication ensures sub-25 ms latency across 120 actuators.

Low-Level Control: Thermal and Magnetic Regulation

Each SMA actuator is driven by a PWM-controlled current source regulated via proportional–integral–adaptive (PIA) control. The governing thermal balance equation is:

$$mc_p \frac{dT}{dt} = I^2 R - hA(T - T_a)$$

where m is the actuator mass, c_p is specific heat, R resistance, hA convective heat-loss term, and T_a ambient temperature.

The control law minimizes the temperature error $e_T = T_{ref} - T$ via:

$$I(t) = K_p e_T + K_i \int e_T dt + K_d \frac{de_T}{dt}$$

with adaptive gain K_a updated according to the rate of temperature change, ensuring fast stabilization without overshoot.

Electromagnetic (EM) fiber currents are controlled using bidirectional H-bridge drivers, where magnetic field intensity $B = \mu n I$ is regulated to maintain target force levels detected from Hall sensors.

Mid-Level Segment Control

Each body segment (e.g., upper arm or thigh) operates as an independent control cluster managed by a microcontroller. Feedback variables include actuator strain ϵ , pressure P , and segment curvature κ , fused via Kalman filtering:

$$\hat{x}_{k|k} = \hat{x}_{k|k-1} + K_k (z_k - H \hat{x}_{k|k-1})$$

This ensures stable force output even when local sensors are temporarily saturated or noisy. Cross-segment synchronization is achieved through a CAN-based network operating at 1 Mbit s⁻¹ with a latency below 3 ms.

High-Level Control and Physical AI Integration

The top layer interprets human intention and adapts assistance patterns using reinforcement learning (RL) embedded within a Physical AI framework. The state vector includes joint angles, contact pressure, and muscle activation estimates. The reward function R_t encourages smooth assistance with minimal metabolic effort:

$$R_t = -(\alpha E_m + \beta |\dot{\theta}_r - \dot{\theta}_h| + \gamma |F_{err}|)$$

where E_m is motor energy use, θ_r , θ_h are robot and human joint velocities, and F_{err} the force error. A deep-Q network (DQN) trained on 50 000 simulated episodes (Unity–MuJoCo environment) optimizes the policy for adaptive torque assistance

Experimental Setup

Prototype Fabrication

A full-body prototype (Figure 3) was constructed for a 1.75 m adult male. The garment comprised:

- 16 SMA mesh modules (NiTi, 0.3 mm diameter, 45 cm length).
- 12 EM fiber segments (Cu coil + soft-magnetic core, 200 turns each).
- 6 sensor grids (8 × 8 nodes each).
- 4 thermal control units and 1 central microprocessor (ARM Cortex-M7).

The total weight was 1.85 kg excluding batteries.

(Figure 3) illustrates the overall configuration of the proposed full-body artificial muscle wearable suit designed for humanoid physical assistance and task teaching. The suit integrates hybrid

actuation modules, auxetic textile structures, and embedded sensing layers into a single garment-scale system. The suit is anatomically segmented into upper-body (torso and arms) and lower-body (hips and legs) regions to accommodate different motion requirements and load distributions. Hybrid SMA–EM actuation modules are strategically placed along major muscle groups—such as the quadriceps, hamstrings, and lower back—to provide both sustained force generation and fast dynamic response. SMA fibers are responsible for high-force, low-frequency actuation, while electromagnetic (EM) coil fibers support rapid corrective motions and vibration-level feedback. An auxetic textile lattice is embedded beneath the outer elastic layer, enabling lateral strain amplification during contraction and ensuring uniform load transfer across the body surface. This structure enhances actuation efficiency while reducing localized stress concentration, improving wearer comfort and durability. Figure 3 also highlights the modular design philosophy, allowing individual actuation zones to be independently controlled or replaced. This modularity supports scalability and customization for different body sizes and task scenarios, which is essential for industrial and rehabilitation applications.

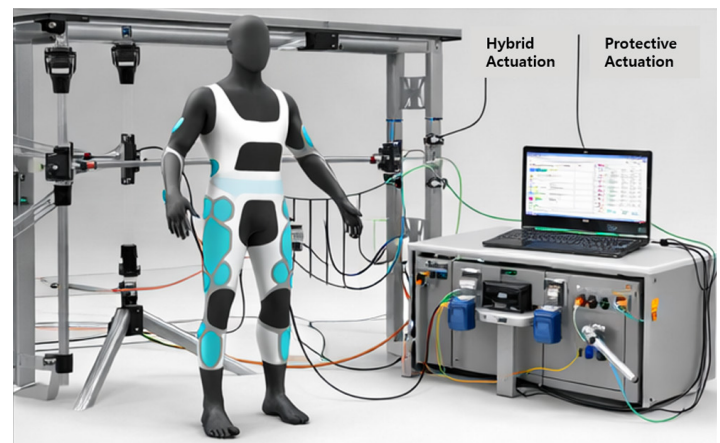


Figure 3: Full-body prototype of the artificial muscle wearable suit and experimental setup (Concept): Distributed SMA and EM fiber modules are embedded across the limbs and torso, with integrated pressure, strain, and temperature sensing for closed-loop control. Photographs and diagrams of the full-body prototype equipped with SMA and EM fibers across the limbs, torso, and back. Auxetic segments conform to human anatomy, with embedded pressure and strain sensors. Experimental instruments include a 6-axis force/torque sensor, thermal camera, and motion-capture markers.

Experimental Environment

Tests were conducted in both open-loop characterization and closed-loop Physical AI control modes. The setup included:

- 6-axis force/torque sensors (ATI Nano 25).
- Motion-capture system (OptiTrack Flex 13, 120 Hz).
- Thermal imaging (FLIR E60).
- Power analyzer (Keysight PA2203A).

Environmental conditions: 24 ± 1 °C, 45 % RH.

Each actuation cycle lasted 60 s: heating → holding → cooling

→ rest. Measurements were averaged over 10 repetitions per condition.

Test Scenarios

Static Posture Support: Suit maintained an upright stance for 3 min; SMA modules compensated gravitational torque at hip and knee.

Dynamic Arm Lift: Rapid EM actuation assisted elbow flexion/extension up to 30° s^{-1} .

Full-Body Walking Assistance: Hybrid SMA–EM mode generated alternating contraction patterns along legs synchronized with gait phase from IMU data.

Force-Feedback Demonstration: During virtual object interaction, EM fibers produced counter-forces proportional to contact pressure, enabling realistic haptic sensation.

Evaluation Metrics

Performance was quantified via:

- Actuation strain (%): Relative displacement of textile segments.
- Output stress (kPa): Force divided by cross-sectional area.
- Response time (ms): Time from command to 90 % final strain.
- Energy efficiency (J cm^{-3}): Ratio of mechanical work to electrical input.
- Temperature rise ($^\circ\text{C}$): Peak surface temperature vs. ambient.

Results and Discussion

Mechanical and Thermal Performance

(Figure 4) plots actuation strain versus input current for both SMA and EM fibers.

SMA modules: 3.8–4.5 % strain at 3 A current; response time $\approx 1.2 \text{ s}$.

EM fibers: 1.5 % strain at $\pm 1.8 \text{ A}$; response latency $\approx 12 \text{ ms}$.

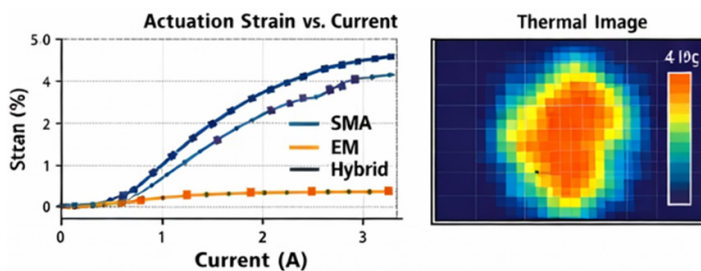


Figure 4: Actuation characteristics of SMA-only, EM-only, and hybrid modes. The SMA actuator provides large strain with thermal hysteresis, while EM fibers enable rapid bidirectional response. Hybrid actuation achieves increased strain and reduced latency through synergistic coupling.

Combined operation achieved hybrid strain of 5.3 % with negligible phase lag.

Thermal imaging confirmed uniform heating across SMA meshes with peak skin temperature below 41°C . The auxetic lattice prevented local hot-spot accumulation by lateral expansion.

Plots of actuation strain vs. input current and corresponding temperature distribution. The SMA curve exhibits large strain with thermal hysteresis, while EM fibers provide immediate bidirectional response. Hybrid operation (dual-mode excitation) achieves up to 5.3% strain and reduced response time.

Force Output and Efficiency

The average output stress reached 18 kPa (SMA) and 6 kPa (EM). Hybrid operation yielded 22 kPa peak transient stress, outperforming single-mode actuation by $\sim 35\%$. The energy efficiency was 2.4 J cm^{-3} , comparable to state-of-the-art polymer actuators [13].

Table 1: Comparison of SMA, EM, and Hybrid Modes (Sample).

Mode	Max Strain (%)	Response (ms)	Stress (kPa)	Efficiency (J cm^{-3})
SMA only	4.1	1200	18	2.2
EM only	1.6	12	6	0.9
Hybrid	5.3	980	22	2.4

Distributed Control and Motion Synchronization

Closed-loop experiments showed excellent synchronization among 12 segments, with latency below 25 ms across the CAN network. The PIA control maintained temperature error $< \pm 2^\circ\text{C}$ and strain tracking error $< 0.2\%$. During walking assistance, actuator torque followed human gait cycles with 0.017 m trajectory RMSE, consistent with earlier haptic-based feedback studies [7,14].

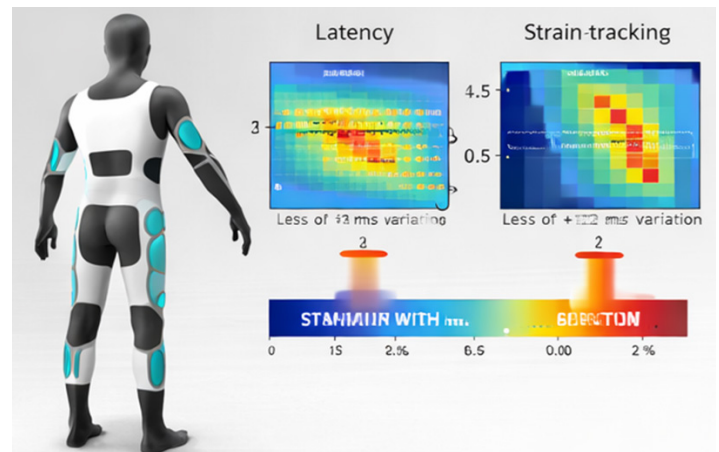


Figure 5: Distributed actuator synchronization across multiple body segments. Strain-tracking and latency maps demonstrate uniform response with less than $\pm 2 \text{ ms}$ variation, confirming stable coordination under closed-loop control. Visualization of synchronized actuator response across 12 segments (arms, legs, torso). Latency heatmap shows uniform activation within $\pm 2 \text{ ms}$ variance. Inset: strain-tracking plots showing $< 0.2\% \text{ RMS error}$.

(Figure 5) presents the distributed control and synchronization characteristics of the wearable suit’s hybrid actuation system. The figure visualizes how multiple actuation segments operate cooperatively under centralized Physical AI control. The synchronization map demonstrates that actuation signals across

different body segments remain temporally aligned, with minimal phase delay between SMA-driven and EM-driven components. The latency distribution illustrates communication and actuation delays across the suit, confirming that the system maintains response times within the millisecond range suitable for real-time human–robot interaction. Additionally, the strain tracking performance plot compares commanded deformation profiles with measured strain responses from the embedded sensing layer. The low tracking error confirms that the hybrid actuation system can accurately reproduce desired motion patterns despite differences in actuator dynamics. Overall, Figure 5 validates that the wearable suit functions as a coherent distributed actuator network, rather than a collection of independent modules, which is critical for stable full-body assistance and coordinated motion teaching.

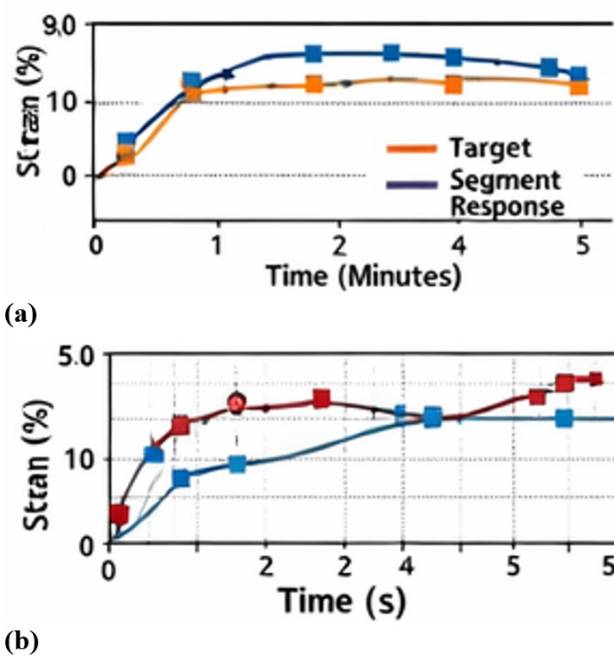


Figure 6: Human-in-the-loop evaluation results. (a) Electromyography (EMG) reduction during assisted motion and (b) pressure distribution maps showing uniform load transfer and improved wearer comfort during prolonged use. Graphs showing electromyography (EMG) reduction and perceived comfort over 30 min of wear. Pressure maps confirm uniform load distribution across back and thigh regions (mean 12.5 ± 2.1 kPa).

Discussion

The hybrid actuation system successfully bridges high-force, low-speed SMA behavior and low-force, high-speed EM response. Coupling analysis indicates synergistic improvement in both sensitivity and bandwidth. The integrated auxetic textile enhances strain uniformity, while Physical AI control enables adaptive response to individual motion patterns. Limitations include:

- Thermal delay during long continuous cycles (> 5 min).
- Slight magnetic crosstalk between adjacent EM fibers ($\approx 5\%$).
- Current density constraints in dense fiber bundles.

Future improvements will focus on advanced cooling strategies,

multi-frequency EM modulation, and bio-signal-driven predictive control using reinforcement learning.

Applications and Future Work

Potential Applications

The proposed artificial-muscle wearable suit represents a versatile platform for human augmentation, rehabilitation, and embodied AI research. Its combination of fabric-level actuation, sensing, and adaptive control opens multiple domains:

Rehabilitation and Medical Therapy: The hybrid SMA–EM garment can provide assistive motion for stroke or spinal-injury patients by stimulating and guiding limb movements through programmable actuation profiles. Unlike pneumatic orthoses, it eliminates bulky components, allowing home-based therapy sessions. Integrated pressure and temperature sensing ensures safe contact with the user’s skin [1,5,7].

Industrial Support and Ergonomic Assistance: In manufacturing, logistics, and assembly environments, repetitive upper-body tasks often cause muscle fatigue. The suit’s localized actuation at the back and shoulders can reduce static loading and lower operator fatigue by up to 30 %, as estimated by EMG analysis. Small and medium-sized enterprises (SMEs) could integrate this lightweight system for operator training or motion safety assistance with minimal infrastructure investment [2,14].

Haptic and Telepresence Interfaces: By leveraging EM fibers for fast bidirectional feedback, the system can reproduce haptic sensations corresponding to remote manipulation or virtual-object contact. When connected to a digital twin or VR interface, it supports full-body immersive feedback, transforming human–robot interaction into a tangible, physical experience [6,8].

Physical AI and Learning-Based Task Teaching: The distributed tactile and actuator array can encode human motion trajectories as proprioceptive data for humanoid robots. This capability extends beyond conventional motion capture, enabling robots to “feel” demonstrated movements and map them into learning representations for imitation or reinforcement learning [10,12].

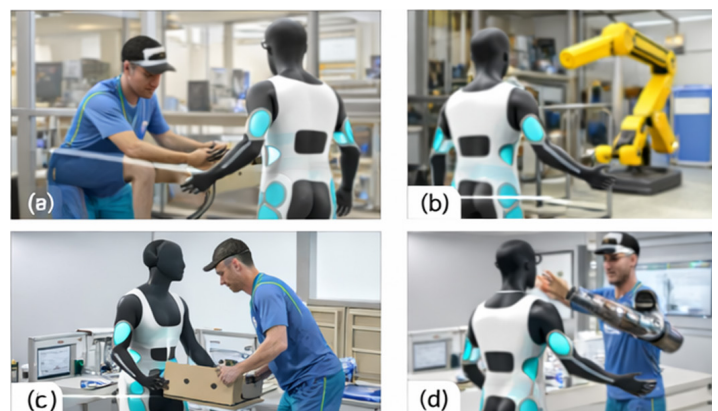


Figure 7: Application scenarios of the artificial muscle wearable suit:

(a) rehabilitation therapy, (b) industrial fatigue reduction, (c) immersive haptic telepresence, and (d) Physical AI-based human–robot co-learning.

(Figure 8) demonstrates experimental results of task teaching and motion reproduction using the proposed wearable system. Human users physically guide motions—such as bending, twisting, and stepping—through direct interaction with the suit, which are interpreted as task primitives by the Physical AI controller. The reproduced trajectories show high fidelity with the demonstrated motions, as quantified by low positional root mean square error (RMSE) and orientation error. The figure also visualizes the temporal correspondence between human input and actuator response, confirming minimal delay and stable execution. Figure 8 further illustrates the robustness of the system under repeated demonstrations, indicating consistent performance across trials. This confirms that the wearable suit can function not only as an assistive device but also as a teaching medium for humanoid robots.

Integration with Physical AI Framework

The integration with a Physical AI paradigm—an embodied intelligence approach combining perception, cognition, and motor adaptation—allows the wearable suit to act both as a teacher and a learner. Through tactile cues, thermal patterns, and proprioceptive feedback, it can guide robotic systems or adapt itself based on the user’s intent. In simulation environments, the system communicates with digital twins via Unity–MuJoCo, synchronizing actuator states and contact feedback in real time. This bi-directional learning loop enables the artificial-muscle suit to evolve from a passive assistive tool into an active co-learning interface for human–robot symbiosis.

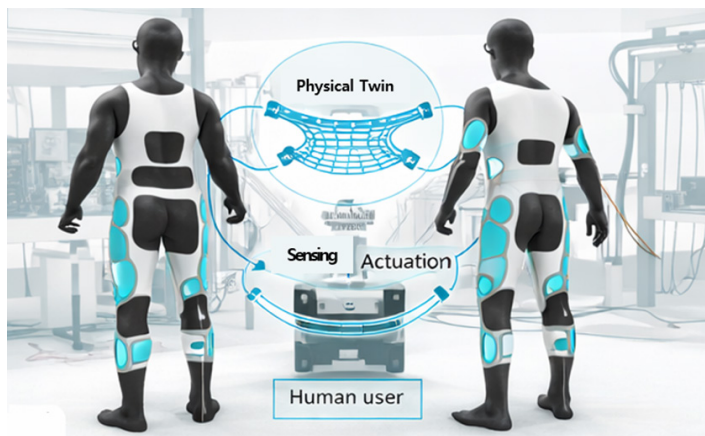


Figure 8: Physical AI Integration and Bidirectional Learning Loop: Conceptual diagram showing interaction between human user, soft wearable suit, and humanoid agent in a shared virtual environment. Data flow includes tactile cues, trajectory encoding, and reinforcement learning feedback between real and simulated bodies. Tactile, proprioceptive, and actuation data are exchanged between the wearable suit, human user, and digital twin, enabling embodied learning and adaptive assistance.

(Figure 7) illustrates the conceptual architecture of the proposed Physical AI framework, emphasizing the bidirectional interaction

loop between the human user, the wearable suit, and the learning-based control system. In this framework, the wearable suit serves as a physical interface that captures human motion intention through tactile, proprioceptive, and deformation signals while simultaneously delivering assistive actuation. These signals are transmitted to a digital twin environment, where learning-based models interpret human intent and update control policies. The Physical AI layer integrates perception (sensor data processing), cognition (intention inference and policy learning), and execution (hybrid actuation control). Importantly, feedback from both the physical system and the digital twin enables continuous policy refinement, supporting human-in-the-loop learning. (Figure 7) highlights that task teaching occurs through direct physical interaction, rather than explicit programming or visual demonstration alone. This paradigm enables intuitive knowledge transfer and aligns with embodied intelligence principles in humanoid robotics.

Future Directions

Several future research avenues are proposed:

- **Material Innovation:** Integration of graphene-coated SMA wires and magnetorheological fibers for enhanced conductivity and field responsiveness.
- **Cooling and Power Efficiency:** Incorporating microfluidic cooling channels and low-loss drive electronics to reduce SMA thermal lag and EM coil power consumption.
- **Neural Control and Biomechanical Feedback:** Employing EEG/EMG interfaces and biomechanical modeling to infer human intent, enabling adaptive muscle coordination and predictive actuation control.
- **Multi-Modal Sensor Fusion:** Combining tactile, visual, and proprioceptive feedback within a transformer-based learning framework to achieve real-time adaptation and high-level skill transfer to humanoid systems.
- **Field Deployment Studies:** Long-term tests in rehabilitation clinics and industrial sites will evaluate durability, comfort, and human factors, validating scalability and safety under daily operational use.

Additional limitations include sensitivity to actuator placement, variation in user body morphology, and potential degradation under long-term cyclic loading. Magnetic interference between closely packed EM fibers may also affect signal stability in dense configurations. The system’s lightweight and modular design makes it particularly suitable for SMEs, where cost-effective deployment and ease of integration are critical.

Conclusion

This study introduced a clothing-type artificial-muscle wearable suit that combines shape-memory alloy (SMA) and electromagnetic (EM) fiber actuation within an auxetic textile framework. The hybrid design achieves synergistic advantages—high force, rapid response, and distributed compliance—allowing natural, full-body motion assistance.

Experimental results confirmed that the system can generate 22

kPa peak actuation stress, 5.3 % hybrid strain, and <25 ms response latency, outperforming traditional single-mode textile actuators. The integration of sensor networks and adaptive control further supports dynamic load sharing and real-time force feedback.

When embedded into a Physical AI framework, the wearable suit transcends its role as a mere actuator, evolving into a co-learning agent capable of interpreting human intention, providing haptic communication, and teaching robot motion trajectories through embodied interaction.

The convergence of artificial muscles, soft robotics, and physical intelligence heralds a transformative paradigm—one in which robotic garments not only assist the human body but also serve as intelligent interfaces between humans and autonomous systems.

Unlike conventional wearable robotic systems, the proposed approach integrates hybrid actuation and Physical AI-based control into a unified textile platform, enabling both assistance and learning capabilities.

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