Application-Oriented Low-Voltage Soft Actuators: Scenario-Based Requirements, Design Strategies, and Evaluation Metrics

Guangsheng Li *

The University of Melbourne, Melbourne, Victoria, Australia

* Corresponding Author Email: Guangshengl@student.unimelb.edu.au

Abstract. Soft actuators with compliant, muscle-like deformation are used in wearable devices and soft robots that operate close to the human body. Typical current soft actuators still rely on kilovolt-level driving voltages, which force the use of large step-up power supplies and thick insulation and raise electric-shock risks, so compact on-body and portable systems are hard to realize. This conflict motivates soft actuators that reach useful deformation and force at operating voltages below or equal 1 kV, with Dielectric Elastomer Actuator (DEA), Hydraulically Amplified Self-Healing/Low-Voltage Electrostatic Actuator (HASEL/HALVE), and Ionic Polymer–Metal Composite (IPMC) as representative examples. For these three families, the working principles are discussed together with low-voltage design choices, and their influence on achievable strain, response speed, and system size is compared. Power-supply miniaturization, electrically safe encapsulation around high electric fields, and efficient use of electrical energy in the complete device emerge as the central constraints when such actuators are built into wearable, medical-rehabilitation, and service-robotic hardware.

Keywords: Low-Voltage Soft Actuators, Dielectric Elastomer Actuators (DEA), Electrohydraulic Actuators (HASEL/HALVE), Ionic Polymer–Metal Composite (IPMC).

1. Introduction

Soft actuators, including dielectric elastomer actuators (DEAs) and the emerging hydraulically amplified self-healing electrostatic (HASEL) actuators, have garnered significant attention in the fields of wearable devices and soft robotics, owing to their high compliance and muscle-like deformation and motion characteristics [1] [2]. However, most current soft actuators still require driving voltages of up to several kilovolts to generate sufficient strain and force output [3]. Such high voltages imply bulky and complex high-voltage power supplies and driver circuits that increase system-integration complexity, and they also entail safety risks such as electric shock and dielectric breakdown, necessitating stringent insulation and protection in applications close to the human body [4]. The requirement for high driving voltage has thus become one of the key bottlenecks limiting the practical deployment of soft actuation technology [1]. Consequently, reducing the driving voltage has become an important research objective in recent years, with the aim of lowering the operating voltage to the kilovolt level or below without significantly sacrificing output performance [2]. In this article, ‘Low Voltage’ is defined as a driving voltage not exceedingly approximately 1.5 kV, with particular attention to ≤1.0 kV. Lowering the driving voltage to the kilovolt range is significant; on the one hand, lightweight and compact power sources (such as battery packs providing several hundred volts) could replace bulky benchtop high-voltage amplifiers; on the other hand, it relaxes insulation and shielding requirements and reduces leakage currents, making it easier to comply with safety standards such as safety extra-low voltage (SELV, typically <50 V [4]) in applications close to the human body. Indeed, several breakthrough studies have validated the feasibility of driving soft actuators at sub-kilovolt voltages [5] [6]. This article reviews recent application-oriented progress in low-voltage soft actuators and summarizes performance requirements and low-voltage design strategies across different application scenarios. It first introduces the main types of low-voltage soft actuators and their working mechanisms, discussing how concurrent advances in materials, actuation mechanisms, and structural design can lower the driving voltage and how these choices affect performance. It then delineates five representative application domains, analysing their specific requirements and representative advances, including wearable haptic interfaces, soft grasping and micromanipulation, rehabilitation aids and human–machine interfaces, bioinspired soft robots (including underwater applications), and humanoid soft robots. The section on system integration and packaging examines engineering issues such as electrical safety and protective encapsulation in the system-level integration of soft actuators. Finally, it summarizes the current challenges facing low-voltage soft actuation and outlines future directions for development.

2. Actuator Classification and Low-Voltage Characteristics

For soft actuators driven in the sub-kilovolt range, the actuation mechanism fixes how the electric field acts in the active material and thus sets the usable voltage range and geometric constraints. In this low-voltage setting, commonly used mechanisms include dielectric elastomer actuators (DEAs), electrohydraulic actuators, ionic actuators, electrothermal actuators, and other types such as magnetic and piezoelectric actuators [1].

2.1. Dielectric Elastomer Actuators (DEAs)

DEAs deform through Maxwell stress: an electric field between compliant electrodes compresses the elastomer in thickness and produces in-plane expansion. Lower driving voltage is mainly obtained by shortening the active thickness of the film and by tuning its permittivity. In one common design, the elastomer is formed into ultrathin layers of about 3–10 µm and stacked into 3–20-layer assemblies, so that considerable strain is reached at 245–500 V [5] [6] [7]. In another group of designs, the dielectric constant is raised by using high-permittivity (high-κ) elastomers or by dispersing highly polarizable fillers into a soft matrix; for the same applied voltage the Maxwell stress and deformation then increase, at the expense of higher elastic modulus and dielectric loss, which enhances heat generation during actuation [3]. In practice, edge breakdown, leakage current and environmental stability often provide the main constraints when DEAs are operated at a few hundred volts. Breakdown tends to start where the electric field concentrates near electrode edges, so electrode corners are rounded and the local field is smoothed to reduce this risk. Current-limiting structures are introduced to keep leakage current in the microampere range and improve touch safety, and material systems with stable thermal and hygroscopic behavior are selected so that the encapsulation can be repaired without significant change in performance. A three-layer 6 µm film delivers pronounced strain below 500 V, and a printed single-layer 3 µm structure achieves about 7.5% in-plane strain at 245 V [5] [6].

2.2. Electrohydraulic Actuators

Electrohydraulic actuators (HASEL/HALVE) operate by using electrostatic stress to deform a liquid dielectric layer, thereby amplifying output via hydraulic effects, and they inherently offer safety through full encapsulation. Classical HASEL devices require several kilovolts; HALVE employs high-k shell materials and multi-chamber structures to reduce unit voltage to approximately 1.1 kV while maintaining 10–30% contraction and high-power density, making it suitable for soft grasping and underwater propulsion [8]. Operating voltage can be reduced by thinning the dielectric layer, using high-permittivity liquids, and optimizing fluid-channel geometry to minimize hydraulic resistance. Additionally, arranging unit cells in series or parallel can enhance overall output while maintaining a low per-unit voltage.

2.3. Ionic Actuators

Ionic polymer–metal composites (IPMCs) and conducting-polymer actuators operate at 1–5 V, where ionic migration induces swelling or bending. This mechanism inherently meets low-voltage requirements, and the constituent materials are typically exceptionally compliant [9]. The performance of these actuators is primarily limited by their response bandwidth and output force density. Because operation is governed by ionic diffusion, the operating frequency typically remains below 1–2 Hz, while the achievable stress and strain are further limited by ion concentration and effective migration pathways. Effective strategies include thinning the active layer, increasing ionic mobility, constructing low-impedance electrode–electrolyte interfaces, and shortening ionic pathways [9] [10]. This actuation route offers distinct advantages for micromanipulation and wearable micro-displacement applications that demand ultralow voltage and small strokes. However, deploying it for joint-level outputs necessitates coordinated advances in both materials and structural design.

2.4. Electrothermal Actuators

Electrothermal actuators, such as twisted-and-coiled actuators (TCAs), shape-memory alloys (SMAs), and liquid-crystal elastomers (LCEs), use electrically induced heating: a temperature rise in the active material causes dimensional or phase changes and produces actuation strain. Reported devices typically employ drive voltages in the 2–24 V range and show large actuation strain [11]. The same heating and cooling processes introduce thermal inertia, which lowers energy efficiency and limits the usable bandwidth to about 0.1–1 Hz [11]. To work within these limits, designs reduce thermal mass, enhance convective heat dissipation, apply pulse or duty-cycle drive schemes, and arrange multiple filaments in parallel to shorten thermal time constants. A biocompatible electrothermal material system operates at approximately 39 °C under 3.6 V and has been demonstrated for near-body actuation [12].

2.5. Comparative Analysis and Discussion

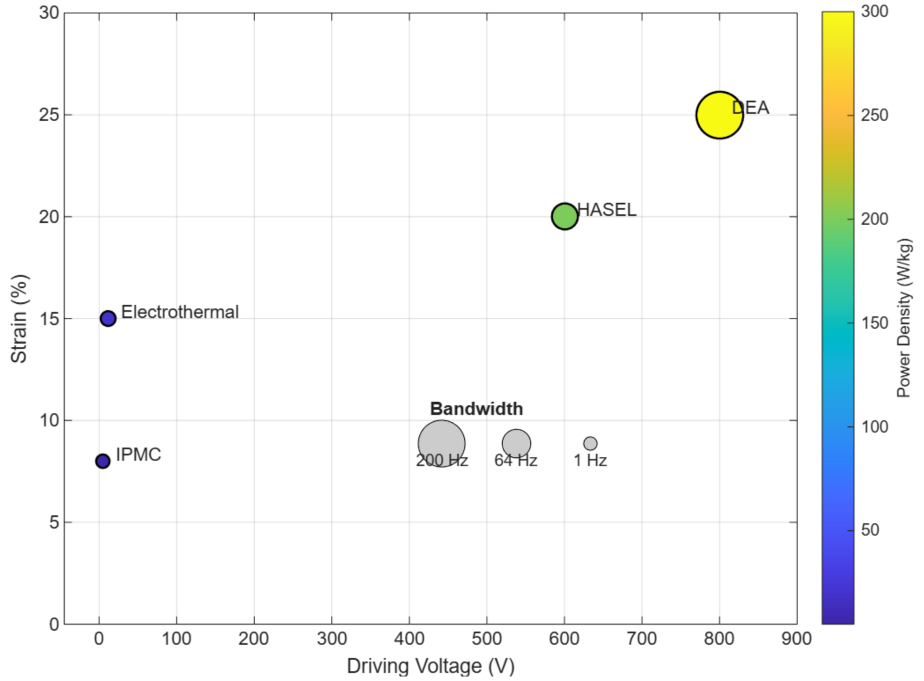

Figure 1. Voltage–Strain Performance of Low-Voltage Soft Actuators. (Picture credit: Original)

Dielectric Elastomer Actuators (DEAs) require 0.5–1.0 kV; under these voltages, reported devices reach 30–100% strain and 100–300 Hz bandwidth, and the corresponding electric fields demand strict insulation and dedicated high-voltage power supplies. HASEL/HALVE actuators share a similar voltage range of 0.5–1.1 kV. Their liquid-filled chambers generate 20–50% strain and substantial force output, and liquid viscosity sets the upper operating frequency [1] [8]. For ionic actuators, the defining feature is the sub-5-V drive: power consumption remains low, and the resulting displacements match the scale needed for micromotions and wearable interfaces. Shape-memory alloys and other electrothermal actuators instead sit in the 2–20 V range; they provide large strain, while low energy efficiency and operational cycle life constrain repeated use at high duty [1] [9] [11].

Ultrathin multilayer DEAs and electrohydraulic amplification have been used to keep DEA-like strain levels while moving operation toward the lower end of this voltage range [1] [8]. Within the ranges above, reported devices show that ultra large strain, high output force, and high bandwidth do not coincide at low voltage [3]. Haptic and other body-proximal devices must satisfy limits on voltage and displacement at the point of contact, whereas joints and grasping mechanisms are constrained mainly by required force and lifetime and often add mechanical amplification to meet these demands [3]. Figure 1 and Table 1 list representative voltage, strain, bandwidth, and efficiency values for the actuation routes discussed here [1] [9].

Table 1. Structural and performance comparison of representative low-voltage soft actuator technologies.

Route & representative literature	Driving voltage (peak)	Film thickness t (or electrode gap)	Typical electric field strength E=V/t (MV·m^{-1})	Maximum strain (%)	Bandwidth (Hz)	η_device (%)	Test conditions (prestrain/environment, etc.)
Multilayer ultrathin DEA [5]	450 V	3 × 6 µm multilayer	~75	20% (in-plane strain)	450 Hz (leg vibration)	~5% (estimated)	5% prestrain; room temperature; ambient air
Ultrathin printed DEA [6]	245 V	3 µm single layer	~82	7.5% (in-plane strain)	1 Hz (stepwise drive)	2–5% (estimated)	No prestrain; room temperature; clamped film boundary
Peano-HASEL actuator [7]	5 kV	~200 µm film + liquid chamber	~25	25% (linear contraction)	<20 Hz	15–20 %	No prestrain; oil dielectric; in air
HALVE electrohydraulic muscle [8]	1.1 kV	~100 µm multilayer shell	~11	20% (linear contraction)	10 Hz (estimated)	~20 %	No prestrain; fully encapsulated liquid; in water/in air
Ionic polymer IPMC [10]	3 V	~200 µm film	~0.015	~5% (bending strain)	0.5 Hz	<1 %	Wet environment; free-end bending
PEDOT conducting polymer [13]	2 V	~50 µm film	~0.4 (ionic migration depth)	5–10% (swelling strain)	<0.5 Hz	~1 %	Electrolyte swelling; room temperature
Twisted-and-coiled fiber [14]	10 V	–	–	20% (contraction strain)	0.1 Hz	0.1 %	Heated to 150°C and cooled in air
SMA wire [15]	24 V	–	–	4% (tensile strain)	0.2 Hz	1–2 %	electrically heated to 70°C and naturally cooled

3. Application Scenarios

The performance requirements and design priorities for low-voltage soft actuators vary significantly across application scenarios. These applications can be broadly categorized into five representative domains: wearable haptic interfaces, soft grasping and micromanipulation, rehabilitation aids and human–machine interfaces, bioinspired soft robots (including underwater systems), and humanoid soft robots.

3.1. Wearable Haptic Interfaces (On-skin Devices)

On-skin haptic systems, including gloves, patches, and vests, integrate actuators into thin, compliant layers placed directly on or very close to the skin. Individual on-skin actuators usually provide 0.1–1 mm normal displacement, corresponding to roughly 5–30% thickness variation, and operate over 1–200 Hz so that textures and vibrations can be reproduced across the relevant frequency range [4]. When many such units form an array, simultaneous actuation increases total electrical power and local heat generation, so power per channel and temperature rise at the skin interface have to remain limited. For devices driven at several hundred volts, leakage current is constrained to the microampere level and conductive parts are separated from the skin by dielectric layers and encapsulation structures [4]. One example following these conditions is a multilayer miniature

Dielectric Elastomer Actuator (DEA) that produces about 0.2 mm vibration at ±300 V and 100 Hz in a haptic display prototype [16]. Compact electrohydraulic actuators based on the Hydraulically Amplified Self-Healing/Low-Voltage Electrostatic Actuator (HASEL/HALVE) concept use liquid encapsulation to define the conduction path and lower the effective voltage at the outer surface [8]. Designs commonly incorporate current limiting, electrical isolation, and robust encapsulation so that leakage under several-hundred-volt drive stays well below commonly cited perception and touch-safety thresholds [4] [8] [16].

3.2. Soft Grasping and Micromanipulation

Typical requirements include moderate strain (20–50%) and gripping forces of 0.5–5 N; microgrippers emphasize millinewton-level forces at a few volts, with operating frequencies commonly 1–10 Hz to enable smooth control. Encapsulation should be compliant, nontoxic, and sterilizable. At <1 kV, multi-unit HALVE architectures in series/parallel can enable safe grasping [8]; multilayer DEAs drive flexible fingers at several hundred volts; and IPMCs/conducting polymers realize micro gripping at a few volts with no magnetic interference, facilitating micromanipulation [9]. A key design guideline is hierarchical technology selection by task scale: electrohydraulic and DEA routes for gripper-level outputs, and IPMCs/conducting polymers for sub-millimeter precision manipulation [8] [9].

3.3. Rehabilitation Aids and Human–Machine Interfaces (Body-proximal Wearables)

Exoskeletons, assistive garments, and prostheses operate close to the body for extended periods and should prioritize SELV—typically <50–60 V, depending on the applicable standard—together with long lifetime (≥10^6 cycles) [4]. Required linear strains are often 10–30%, unit tensile/compressive forces 10–100 N, and the bandwidth of human motion is comparatively modest (0–5 Hz). Available actuation technologies present distinct trade-offs. Flexible-fiber DEA bundles offer rapid response but typically require several hundred volts. IPMCs and conducting polymers operate at just a few volts and are well-suited for body contact, although their present force density remains relatively low [9] [13]. SMAs and shape-memory polymers (SMPs) function at low voltages but are limited by low efficiency and slow response, making them suitable primarily for slow-speed assistance [11]. A practical path is hybrid actuation—combining soft actuators with motion-amplifying mechanisms or elastic energy-storage elements to provide sufficient assistive joint torque within safe voltage limits [4] [9] [11] [13].

3.4. Bioinspired Soft Robots (Including Underwater)

For bioinspired systems such as crawling, swimming, and tentacle-like platforms, the emphasis is on low voltage under onboard power and task-specific deformation (10–100%, depending on the mission). At the insect scale, ultrathin multilayer DEAs are applicable—for instance, DEAnsect achieved autonomous walking under <450 V with onboard power [5]; at the moderate scale, HALVE attains muscle-like power density at ~1 kV to drive fins or soft trunks [17]. Actuation–mechanism coupling should be selected according to task frequency—crawling at a few hertz, fin/wing oscillation at tens to >100 Hz—and environmental robustness should be enhanced through waterproofing, sealing, and impact-resistant encapsulation [5] [8] [17].

3.5. Humanoid Soft Robots

Humanoid scenarios target close human–robot interaction, with touch-safe voltage typically requiring SELV levels (<50–60 V) [4], while demanding muscle-like deformation (10–30%, or the corresponding joint angle via mechanisms) and force levels (unit stress 0.1–1 MPa, joint resultant forces of tens to hundreds of newtons). Current systems often adopt hybrid rigid–soft actuation, where motors provide baseline force and soft actuators deliver compliant, safe end-effector interaction; there are also explorations using sub-kilovolt multilayer DEA arrays to achieve hand-like bending and grasping [18]. At the system level, requirements include electromagnetic compatibility, power segmentation, redundancy with fault isolation, and flame-retardant materials with verified long-term reliability [3] [4] [18].

Table 2. Specific requirements for actuator performance in each application scenario

Application scenario	Target driving voltage	Required strain amplitude or stroke	Force/stress requirement	Response speed/bandwidth	Encapsulation and safety requirements	Preferred actuation route
Wearable haptic interfaces	<1 kV (ideally <500 V, battery powered)	5–30% thickness change (0.1–1 mm displacement)	Tens of mN force output (per unit)	1–200 Hz with tunable vibration bands	Complete insulation for electrodes and leads; skin-contact biocompatible materials; leakage current <10 µA; sweat and water protection (IP67)	Multilayer miniature DEAs; HAXEL/HALVE microactuator units; Conducting polymer gels (small-strain haptics)
Soft grasping and micromanipulation	<1 kV (wired power acceptable))	20–50% bending or contraction	0.5–5 N gripping force (finger level) or mN-level microforces (micromanipulation)	1–10 Hz motion frequency	Waterproof and dustproof encapsulation using food-grade or medical silicone; Compliant, non-damaging contact with grasped items; Nontoxic and sterilizable for medical micromanipulation	Series–parallel HALVE actuators (soft grippers); Multilayer DEAs (flexible fingers); IPMC or CP actuators (microgrippers)
Rehabilitation aids and human–machine interfaces	<100 V (ideally <50 V, battery powered)	10–30% linear strain (artificial muscle)	10–100 N tensile or compressive force (joint-assist level)	0–5 Hz slow repetitive motion	Double insulation for body-worn actuators; Lifetime >10^6 cycles under long-term repetition; Medical electrical safety (IEC 60601)	Flexible fiber DEA bundles (carbon nanotube muscles); High-performance IPMC (low-voltage micro-power); SMA or shape-memory polymers (modest assistance).
Bioinspired soft robots	<1 kV (lower is better, onboard power)	10–100% deformation depending on the task	0.1–1 N thrust (small crawling or swimming) and 1–10 N (medium soft robots)	0–50 Hz (crawling at a few hertz, wing or fin flapping up to hundreds of hertz)	Housings resistant to water, dust, and compression; Elastomeric sealing and isolation for high-voltage parts; Certain risk acceptable in uninhabited environments	Ultrathin multilayer DEAs (micro-scale insect robots); HALVE or HASEL (medium-scale bioinspired fish and soft arms); Magnetic or piezoelectric auxiliary actuation (special scenarios).
Humanoid soft robots	<50 V touch-safe voltage	10–30% linear strain (artificial muscle) or joint angles via mechanisms	50–200 N forces (large-joint resultant) with unit stress 0.1–1 MPa	0–10 Hz for large-amplitude motions and 0–100 Hz for small oscillations	System integration requiring electromagnetic compatibility with sensing and electronics, multi-unit redundancy with fault isolation, flame-retardant materials, and long-term reliability	Artificial muscle arrays (high-density DEA fibers); Soft hydraulic tendons (low-voltage fluidic combinations); hybrid motor–soft actuation (a transitional approach at present).

For representative scenarios such as wearables, rehabilitation aids, and bioinspired robots, the performance targets and safety requirements of low-voltage soft actuators differ. The discussion further consolidates target thresholds and corresponding technical routes for different applications, as summarized in Table 2, to support engineering selection and system integration.

4. System Integration and Packaging

Low-voltage soft actuators are driven by electric fields on the order of several hundred volts at the device, even when the power source is a low-voltage supply. To generate these fields, the electrical part of the system contains at least three functions: a step-up converter, a power stage, and a signal-modulation interface. Each function takes board area, thickness, and clearance on a rigid or flexible substrate, which directly limits how small the electronics can be made in wearable devices and small robots [19]. Micro high-voltage converters and switching arrays on MEMS or flexible substrates have been demonstrated; in these circuits, several-hundred-volt outputs are produced directly on patch-type flexible electronics instead of on separate rigid printed-circuit boards [19]. At the wiring level, the voltage difference between actuator leads and nearby low-voltage circuitry sets requirements on insulation thickness, spacing, and, where needed, shielding. Layouts that route high-voltage lines close to sensors or analog front ends add shielding layers or increase separation to limit coupling. When many actuator units are arranged in an array, each unit and its driver form a possible fault point, so isolation between channels and redundant paths in the wiring are used to keep a local failure from disabling the remaining actuators. Housings, substrates, and encapsulant layers must tolerate long-term electrical stress, repeated bending, and heating, and they often need flame-retardant behavior when required by the intended use. Packaging/encapsulation plays a critical role in the safe operation of the overall system. In body-proximal or outdoor applications, actuators and their electrodes should be encapsulated with flexible silicones or polymer films to provide ingress protection and to prevent contact with live parts. Prior work has fully encapsulated dielectric elastomer actuators (DEAs) and hydraulically amplified self-healing electrostatic actuators (HASELs) in biocompatible silicone, achieving IP67-rated protection such that—even with internal potentials of hundreds to over a thousand volts—the external surface can remain touch-safe [8]. Packaging should also manage heat dissipation and provide stress buffering to extend service life under repeated deformation and thermal excursions. Nevertheless, while low-voltage design reduces the size and safety burden of drive modules, implementing complex functionality often depends on multi-degree-of-freedom actuator arrays comprising numerous units. This reliance introduces additional challenges in system control and energy management. For example, Ji et al. developed an insect-scale soft robot integrating micro batteries and a step-up circuit to power multiple DEA leg actuators, achieving fully autonomous locomotion [5]; a haptic-vest prototype partitions and drives hundreds of micro-DEA units via flexible driver boards that manage high-voltage outputs across zones, enabling wearable, large-area haptic feedback [16]. In these systems, actuator mechanics, required field strength, wiring layout, and encapsulation thickness are linked. Higher target fields push converter designs toward larger voltage ratios and demand longer creepage distances or thicker insulation; thicker encapsulation changes bending stiffness and heat flow and thereby affects fatigue and temperature rise; arrays with many degrees of freedom fix the number of driver channels and switching elements and shape how electrical power is distributed in time. When a soft-robotic platform is specified for a given use case, materials, device geometry, drive circuitry, and packaging are chosen under these combined constraints from electrical safety, motion and force requirements, and expected lifetime.

5. Conclusion

In the sub-kilovolt range, multilayer ultrathin Dielectric Elastomer Actuators (DEAs) and electrohydraulic actuators such as HASELs provide large strain and high-power density when driven at 0.5–1.0 kV with appropriate insulation and high-voltage supply design. Ionic and electrothermal actuators instead work at 1–5 V or 2–24 V, can be implemented with biocompatible material systems, and their output density and bandwidth are set by ion-transport or thermal time constants. Lowering the drive voltage reduces the conversion ratio demanded of the power supply, shortens creepage and clearance distances, and allows smaller packages, which directly affects electrical safety and long-term use in body-proximal devices. Reported soft-robotic systems based on these actuators are mainly demonstrated in wearable and adherent haptic interfaces, lightweight assistive elements, healthmonitoring patches, and low-disturbance manipulators operating in fragile environments and ecosystems. In these designs, soft actuator layers are mounted on or near the body or specimen and used together with rigid frames or tools; they conform to local geometry, moderate contact forces, and provide locations where sensing and actuation are placed close to the interaction region rather than replacing rigid actuators as the primary load-bearing elements. At the system level, several requirements appear repeatedly. Distributed micro-actuator arrays are used so that mechanical output is obtained by summing many low-voltage units. Power electronics are specified to meet SELV (Safety Extra-Low Voltage, typically <50–60 V DC, depending on the standard) where required and incorporate current limiting, isolation, and shielding so that exposed conductors satisfy electrical-safety constraints. Self-sensing or integrated sensing channels support closed-loop control, and testing increasingly follows defined tasks and loading patterns so that different actuator technologies can be compared under similar conditions. A set of engineering targets follows directly from these points. Wearable and adherent systems considered here operate at ≤500 V with microampere-level leakage currents and cycle lives on the order of 10^6–10^7. Arrayed haptic interfaces and lightweight assistive devices use bandwidths in the 10–300 Hz range with repeatable calibration of displacement or force. Ecological and medical applications are designed to satisfy the specified IP ratings and to obtain the necessary biocompatibility certifications before deployment. Within this actuator set, DEAs and HASELs cover the region of higher strain, force, and bandwidth in the sub-kilovolt regime, whereas Ionic Polymer–Metal Composite (IPMC) devices and electrothermal actuators operate in the ultralow-voltage, low-power regime with relatively simple control, which matches safety- and energy-sensitive scenarios. For low-voltage operation, the dominant limitations now arise from system integration and packaging: reliable high-voltage insulation, thermal management compatible with deformable structures, and environmental protection over long service times. Work on compact high-voltage drive electronics, structural amplification that increases stroke and force at low voltage, and long-term reliability and engineering validation under realistic duty cycles forms the main engineering workload separating current prototypes from robust systems outside the laboratory.

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