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Review

Shape Memory Alloy Actuators for Upper-Limb Prosthetic Applications: A Review

Zheng Deng[1,2,3], Tian Yang[1,2,3], Hongliu YU[1,2,3], Qiaoling Meng[1,2,3,*]

[1]Institute of Intelligent Rehabilitation Engineering, University of Shanghai for Science and Technology, Shanghai, 200093, China

[2]Shanghai Engineering Research Center of Assistive Devices, Shanghai, 200093, China

[3]Key Laboratory of Neural-Functional Information and Rehabilitation Engineering of the Ministry of Civil Affairs, Shanghai 200093, China

[*]Corresponding author: Qiaoling Meng, mql@usst.edu.cn

Abstract

Nickel-titanium (NiTi) shape memory alloy (SMA) actuators have attracted considerable interest in upper-limb prosthetic design because they can produce useful motion within compact and quiet mechanisms. However, results obtained from isolated SMA wires or springs do not always represent their performance in a complete prosthetic system, where cooling, packaging, control hardware, and user safety must also be considered. This review examines thermally activated SMA actuators used in upper-limb prostheses and related wearable devices. Applications of superelastic NiTi are considered separately when the material functions as a passive structural component rather than a heat-activated actuator. The reviewed systems are organized according to actuator configuration and application, including straight wires, coiled springs, antagonistic arrangements, and hybrid designs. The available evidence shows that slow cooling, thermal hysteresis, fatigue, sensing drift, and surface-temperature limits continue to restrict repeated or sustained operation. Thermally activated SMA is therefore better suited to intermittent and space-constrained functions, such as individual finger motion, occasional wrist positioning, and compact locking or release mechanisms. Motor-driven systems generally remain more appropriate for rapid and repetitive grasping. Hybrid systems may provide a practical alternative by assigning frequent motion to motors and reserving SMA for functions in which compact size, quiet operation, or local compliance provides a clear system-level advantage.

Keywords

Shape memory alloy, Nickel-titanium, Prosthetic hand, Artificial muscle, Upper-limb prosthesis

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1. Introduction

Upper-limb prostheses are required to realize effective grasping and positioning while satisfying lightweight, low-noise, safe and energy-saving demands. Increasing the number of degrees of freedom (DOF) can improve functional diversity, but it simultaneously raises the quantity of actuators, wiring complexity, heat emission, acoustic noise and maintenance costs [1]. Accordingly, the performance of prosthetic devices cannot be assessed merely by output force or movement range; system-level indicators including hand weight, closure speed, controllable DOF, battery life, reliability and failure characteristics ought to be comprehensively taken into account [2].

Because of mature control algorithms, continuous motion output and favorable response bandwidth, motor-driven mechanisms dominate main applications among diverse driving schemes for prosthetics. However, the problem is that motors, gear reducers, bearings and transmission assemblies occupy limited internal space and add extra mass to the distal end, especially for miniaturized prosthetic fingers and partial-hand prostheses. These drawbacks drive researchers to develop alternative actuators featuring compact layout, silent operation and biomimetic kinematics.

In this research context, shape memory alloy (SMA) has drawn extensive research interest. Electrically driven SMA wires and springs produce recovery force with minimal moving parts. They have the characteristics of flexible layout and wiring, silent driving, strong inherent adaptability, and strong work-specificity. The above merits can be used to develop prosthetic fingers, robotic hands, wrist assemblies, wearable artificial muscles and superelastic supporting structures [3,4]. However, the application of SMA systems is limited by slow heat dissipation, thermal hysteresis, a narrow bandwidth, fatigue degradation, temperature-sensitive mechanical properties and complicated control logic [5].

This review focuses on thermally activated SMA as an active actuator for upper-limb prosthetic systems and closely related wearable devices. Passive superelastic NiTi structures are retained only as a separately labeled boundary case because their function is mechanical compliance or energy dissipation rather than heat-driven motion. The analysis emphasizes system architecture, measurable trade-offs, and task-specific applicability rather than material properties in isolation.

The original reference corpus was supplemented by targeted searches of IEEE Xplore, PubMed, ScienceDirect, SpringerLink, Wiley Online Library, and Google Scholar from database inception to 15 July 2026. The principal query combined (“shape memory alloy” OR SMA OR NiTi) with (prosthe* OR “artificial hand” OR finger OR wrist OR elbow OR exoskeleton OR wearable OR rehabilitation) and (actuat* OR control OR hysteresis OR thermal OR fatigue OR “self-sensing”). A second query combined “shape memory alloy actuator” with (Preisach OR Liang OR Brinson OR Duhem OR “reduced-order” OR observer OR control). Benchmark searches combined (“prosthetic hand” OR “hand exoskeleton”) with (motor OR pneumatic OR “series elastic”) and (force OR torque OR mass OR response OR power). Backward and forward citation tracking was also used.

We included only peer-reviewed, English-language studies that met one or more core inclusion criteria. Qualifying work must examine thermally activated NiTi actuators built for upper-limb prostheses or wearable upper-extremity systems with clear design transferability. Eligible papers also needed to report actionable system-level data, covering actuator layout, control strategies, thermal management, cyclic fatigue behavior, self-sensing performance, or overall functional outcomes. Studies that provided comparative benchmark data on alternative upper-limb actuation technologies were also retained. Pure superelastic SMA research was only included if it addressed passive structural prosthetic functions, with such cases explicitly noted in our analysis. We strictly excluded several categories of literature: magnetic SMA and shape-memory polymer studies, devices designed exclusively for lower-limb use with no upper-limb applicability, standalone metallurgical research unrelated to actuator implementation, non-peer-reviewed content, promotional material, and studies with incomplete or methodologically unsound experimental protocols.

Initial screening began with 63 references retrieved for this review. After deleting two duplicate entries, 61 unique records remained for preliminary evaluation. A follow-up full-text search identified another 18 relevant articles. Upon detailed manual assessment, seven of these papers were excluded. Eliminated works included two studies investigating non-thermal or magnetic SMA variants, one study limited exclusively to lower-limb applications, two purely material-level investigations that could not translate to prosthetic actuator design, and two non-peer-reviewed or methodologically inadequate reports. The remaining 11 eligible articles were incorporated into the dataset. This process yielded a final collection of 72 unique references for the review.

We manually extracted core parameters from all device-focused studies: the target application category, whether the SMA served as an active thermal actuator or passive superelastic structural component, actuator layout, total system mass, peak force, torque and payload capacity, joint range of motion and contraction travel, response speed and operating cycle frequency, power draw, measured temperature rise and verified duty cycle limits, associated auxiliary hardware, plus the overall validation scope of each study. Missing data entries are marked “NR” (not reported). We avoided forced normalization of raw values when key context was absent—including SMA active length, moment arm geometry, total wearable enclosure size, auxiliary hardware mass, and full test boundary conditions. All such data are reproduced directly from the original publications, rather than converted to a standardized metric without proper context.

2. SMA Actuation Principles and Applications

2.1 SMA Actuation Mechanisms

NiTi shape memory alloys possess two mechanisms that are suitable for prosthetic actuation: the shape memory effect and superelasticity. Under thermal excitation, NiTi undergoes phase transition between low-temperature martensite and high-temperature austenite. Heating across the transformation range causes prestressed SMA wires or springs to return to their pre-trained shape, thus producing an output force and displacement. After cooling, the material is in the martensite phase, and thus external bias elements (springs, tendons, elastic joints, external loads or antagonistic actuators) generally need to be employed to return the actuator to its original position. On the other hand, superelasticity is due to stress-induced martensite formation above the austenite finish temperature; it can undergo large reversible deformation and hysteretic energy dissipation without electrical heating [5,6].

The two mechanisms undertake distinct functional roles in upper-limb prostheses. Thermally activated SMA units serve as active drivers to generate joint motion, while superelastic SMA structures act as passive flexible components, resetting mechanisms, overload protectors or shock-absorbing joints. The two functions are not the same: active SMA actuation is achieved by heating and cooling cycles, and superelastic parts are used mainly for structural rigidity, flexibility and shock absorption.

SMA actuation performance arises from tightly coupled electrical, thermal and mechanical fields. Joule heating due to current input raises the temperature of the material and thus induces a phase transition; simultaneously, resistance, temperature, phase fraction, stress and strain change synchronously. Applied loads shift the phase transition temperatures, and together with ambient airflow, packaging encapsulation, environmental temperature, loading history and contact status, they modify the transient response characteristics. Such coupling introduces non-linearity and thermal hysteresis in SMA actuators, as well as strong sensitivity to operating conditions; thus, high-precision control is much more difficult for these compared with standard motor-driven systems [5,6].

A typical engineering trade-off is that the output force, stroke, dynamic response, energy efficiency and service life are all interdependent and cannot be optimised independently. Larger-diameter wires or bundled SMA units have a higher output force but also generate more heat and are more difficult to cool. Geometric amplification extends the range of joint motion at the expense of structural stiffness and output force. A larger transformation strain can increase the single-cycle working capacity but will reduce cyclic fatigue life [7,8]. The above trade-offs are more prominent for upper-limb prostheses, and actuators need to operate in a confined space while satisfying the demands for a high grasping force, rapid response speed, thermal safety and a long-life battery.

The general reason for reduced performance of SMA is poor heat dissipation. Increase the input power to heat it up more quickly, but for actuator reset, sufficient heat dissipation of the SMA material is required. Thin SMA structures have a higher surface-area-to-volume ratio and are thus cooled down more rapidly; on the other hand, thick or bundled SMA assemblies have a stronger force but cool slowly and unevenly [9]. Auxiliary methods for active cooling, heat sinks and duty-cycle regulation can extend the operating range, but they will generally increase the weight, volume, power consumption or operating noise of the system. Therefore, in the feasibility study of the application of smart actuators in prosthetics, thermal management design should also be included.

Thermal hysteresis represents another non-negligible property. Prosthetic grasping generally has only partial SMA activation, interrupted clamping and minor repetitive position adjustments, it does not complete a full heat-cooling cycle. In such scenarios, the correlations among temperature, resistance, force and displacement follow minor hysteresis loops instead of stable primary loops. If control algorithms adopt ideal cyclic assumptions, position deviation, force drift and excessive heat accumulation will occur. Therefore, the control framework for the SMA prosthetic system should consider thermal history, external loads and thermal safety margin.

SMA actuators are small in size, silent, and compliant; thus, they are promising for prosthetic design. Nevertheless, their performance is limited by thermal response lag, hysteresis loss, cyclic fatigue and multi-field coupling between material properties and system architecture. The intrinsic material properties of these components are the basis for the development of various SMA actuator designs (wire, spring, antagonistic and hybrid structures), which will be introduced in the following sections.

2.2 SMA Actuator Configurations

SMA actuators have many different structures for strain-to-motion conversion. The four main schemes for upper-limb prostheses are straight-wire, coiled-spring, antagonistic and hybrid SMA systems, as shown in Figure 1. These layouts are not just different shapes of SMA; they also have various compromises among their design trade-offs balancing output force, actuation stroke, dynamic response, reset mode, packaging size and serviceability.

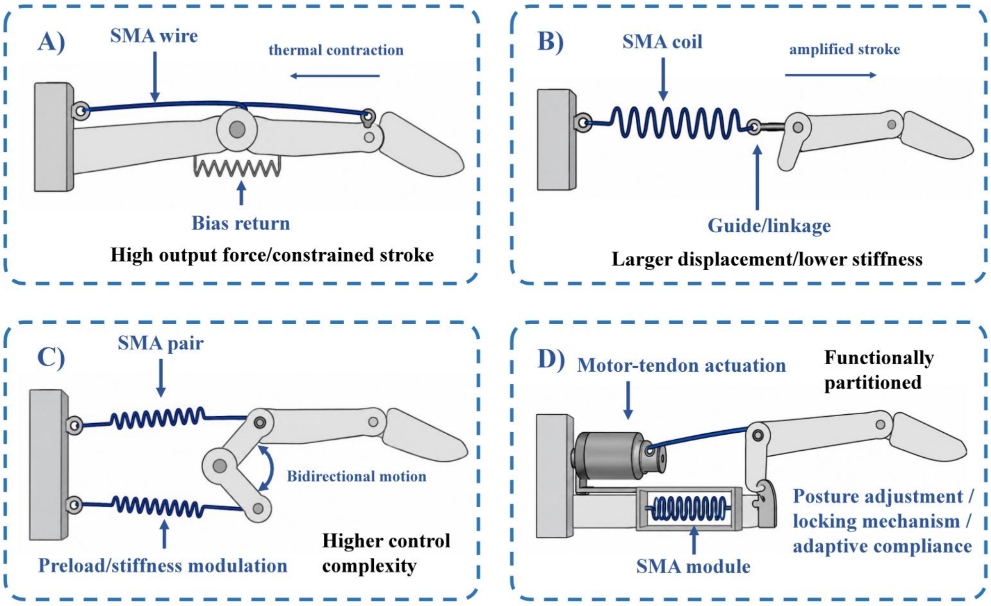

Figure 1. Representative SMA actuator configurations for upper-limb prosthetic applications. A) Straight wire actuator; B) SMA spring actuator; C) Antagonistic SMA actuator; D) Hybrid SMA-based actuator.

Straight-wire SMA represents the simplest and most prevalent layout. Pre-tensioned wires contract due to a rise in temperature and are reset by passive elastic components, such as tendons, compliant joints, external forces or counteracting devices. Their slender cross-section can be placed inside a narrow cavity for routing, and parallel-wire bundles can increase the output force; thus, they are suitable for miniaturized prosthetic fingers, thumb-positioning devices, and tactile-assistance modules. Early studies have shown that distributed SMA wires can be used to build anthropomorphic multi-finger hands without a large gearbox [10-13]. However, straight wires deliver limited recoverable strain, and bundled arrangements suffer from uneven heat dissipation. Such characteristics render them suitable only for low-duty compact operations instead of high-frequency repetitive grasping.

To tackle the short-strain drawback of straight wires, coiled SMA springs have been extensively explored. Wire winding transforms tiny intrinsic strain into substantial axial displacement via bending and torsion, which fits soft prosthetic hands and wearable aids requiring large motion within a compact axial space. Prototypes including 3D-printed coiled-SMA hands and soft biomimetic grippers have verified the practicability of spring-driven lightweight grasping [14,15]. Unfortunately, extended stroke comes at the cost of reduced structural stiffness and force density; spring performance is also highly sensitive to coil geometry, preload and heat distribution. Accordingly, SMA springs excel at lightweight large-displacement mechanisms yet suffer poor repeatable force control and limited long-term durability.

Antagonistic SMA layouts are developed to realize bidirectional biomimetic movement. Such setups consist of two opposing SMA units, or one SMA paired with a passive spring, to drive bidirectional joint motion. This structure imitates human flexor-extensor muscle groups and achieves adjustable joint position and stiffness by regulating the activation level of each SMA element. Antagonistic wire-spring fingers and modular SMA grippers have been used in prosthetic and bio-inspired manipulators to this day [16]. However, antagonistic architectures have additional thermal coupling states, higher control difficulty and consume extra energy under co-contraction. Therefore, they are only suitable for applications that require both bidirectional compliance and stiffness modulation, and passive reset mechanisms are still more economical for unidirectional finger flexion.

Hybrid SMA architectures mitigate the inherent drawbacks of single SMA actuation via functional division among multiple components. SMA undertakes compact posture tuning, stiffness switching, locking and release tasks, while motors, tendons and elastic structures undertake cyclic movement and load bearing. Representative prototypes, such as motor-SMA composite fingers, SMA wrist assemblies, self-locking grippers and Nitinol-reinforced palms, demonstrate how SMA integration optimizes compactness and passive compliance [17-20]. Hybrid design lowers thermal load on SMA components and elevates overall system performance, yet it introduces extra mechanical interfaces, calibration procedures and potential failure points.

In general, the evolutionary progression from straight wires to coiled springs, antagonistic pairs and hybrid layouts reflects continuous efforts to offset SMA's intrinsic actuation limits. Straight wires have a simple structure and high routing density; coiled springs extend the actuation stroke; antagonistic structures achieve biomimetic bidirectional motion; and hybrid layouts are task-oriented integrations. None of the above schemes can address the underlying problems of thermal lag, hysteresis, fatigue loss and high energy consumption. Consequently, SMA layout selection should depend on target prosthetic functions, duty cycles, required force-stroke ranges, allowable surface temperature and maintenance schemes, rather than material compactness as the sole criterion.

2.3 Typical Prosthetic Applications

Early work progressed from a mechanically designed SMA prosthetic hand in 2002, through distributed actuator concepts in 2005 and an anthropomorphic hand in 2008, to integrated nonlinear control of a multifunctional hand in 2014 [10-13]. These studies established the baseline challenges–limited cooling, nonlinear hysteresis, transmission packaging, and repeatability that remain visible in recent high-DOF systems.

The upper-limb evidence spans four application classes: terminal prosthetic hands or digits, wrist/elbow wearable devices, textile SMA gloves or artificial muscles, and passive superelastic structural systems. Prosthetic hand studies emphasize compact routing, distributed actuation, thumb positioning, and compliant grasping [21,22]. Wearable wrist and elbow systems benefit from longer active lengths and more heat-exchange area, whereas textile platforms prioritize conformability. Passive superelastic structures are a separate structural category rather than a thermal actuator category.

Distal hand prostheses face the strictest spatial and thermal restrictions. Fingers and partial-hand devices have confined internal cavities for actuators, wires, thermal insulation, sensors and cooling assemblies. Straight SMA wires can be placed along phalanges or tendon channels, and coiled SMA springs are commonly arranged in the palms or forearms and connected to the digits by transmission linkages [23-26]. Remote mounting reduces the distal mass and isolates heat sources, but introduces extra friction, structural compliance and variable moment arms. Therefore, SMA is suitable for intermittent finger movements, thumb opposition, miniature locking units and superelastic flexible frameworks rather than continuous high-speed forceful grasping. A 19-DOF prosthetic hand integrated 38 SMA actuators, sensing, forced-air cooling, and on-board power within a 370 g system, demonstrating a 2.5 kg reported maximum load and a 27.2 °C socket-interior temperature after 30 min of continuous use [23].

Wrist and hand wearable devices offer a larger design space for SMA integration. SMA wrist-forearm exoskeletons and tendon-driven assist gloves are compact and conformal in terms of wiring and body fitting [27,28]. Coiled SMA artificial muscles are used to generate a 1.32 N·m flexion torque in a lightweight 151 g, 2-degree-of-freedom wrist aid [29]. Hand exoskeletons, knitted SMA gloves, pre-detwinned spring muscles and woven zigzag actuators have also achieved large stroke and flexible packaging with an adequate heat exchange area [30-33]. These platforms offer reference information for the arrangement of actuators and thermal management design, but their test results cannot be directly applied to the entire clinical verification of a prosthesis.

Wrist and elbow possess larger installation space but demand higher output torque. Elongated SMA artificial muscles and distributed wearable drivers have longer active lengths and wider heat-exchange surfaces than tiny finger modules, thus achieving better stroke and heat dissipation [34]. Wrist alignment and elbow support still need to provide continuous torque to offset gravity and other load components. Continuous thermal excitation of SMA wastes energy in maintaining a static posture; mechanical latches, self-locking transmissions, elastic balance structures and motor-SMA hybrid schemes are feasible alternatives. Therefore, SMA is more suitable for intermittent pose tuning and stiffness regulation rather than long-term load-bearing drive.

Performance priorities also vary by function. Finger flexion tolerates modest position error if stable contact force is maintained; thumb opposition requires repeatable pre-shaping; and wrist adjustment is infrequent but must resist external moments after positioning. These tasks should not be ranked using one universal force or speed threshold. Table 1 explicitly classifies the representative SMA-based upper-limb prosthetic or bio-inspired systems and reports the same metric fields for every entry; NR is used when the source did not provide a value.

In short, the existing prototypes show that SMA is suitable for small, quiet, and intermittent operation in upper-limb prostheses and wearable aids, especially for partial finger movement, thumb opposition, low-cycle wrist regulation, flexible supporting frames, and hybrid auxiliary modules. SMA is relatively weak in high-frequency repetitive grasping, continuous high-torque operation and extended static retention due to inadequate heat dissipation; therefore, there is a risk of thermal damage and high power consumption. Future research on SMA prostheses should carry out all-round assessments in a realistic operational environment, such as battery life, repeated use cycles, and human thermal safety.

Table 1. Representative SMA-based upper-limb prosthetic or bio-inspired systems

Application class	Study / year	SMA role and configuration	System mass	Output metric	ROM / contraction	Response / rate	Power / thermal evidence	Evidence scope
Terminal prosthetic hand	Andrianesis & Tzes [13], 2014	Active thermal; straight wires	NR	Multifinger actuation; non-normalized	NR	NR	NR	Integrated hand and nonlinear control
Terminal prosthetic digit	Gao et al. [17], 2015	Active hybrid; SMA + DC motor	NR	Source-specific finger output	NR	NR	NR	Functional allocation between SMA and motor
Terminal prosthetic actuator	Taylor & Au [35], 2016	Active wire array + forced air	NR	Position settled error ≈15 µm	NR	Cycle interval 9.5→3.5 s	Forced-air cooling; power NR	Cooling bench integrated with prosthetic actuator
Terminal soft hand	Simone et al. [24], 2020	Active 100-µm wire bundles + passive superelastic joints	NR	9 N per finger	Tip 45°; middle/base phalanges 90°	NR	NR	Integrated five-finger prototype
Terminal soft hand	Deng & Tadesse [14], 2020	Active coiled SMA	235 g	133 g payload (≈1.30 N weight)	NR	0.125 Hz	7.82 W; temperature NR	Integrated 3D-printed hand
Terminal prosthetic hand	Yang et al.[23], 2025	Active antagonistic spring pairs + tendons + forced air	370 g total; 220 g hand part	2.5 kg reported maximum load	19 DOF	~1.3 s command-to-activation	Socket interior 27.2 °C after 30 min; electrical power NR	Integrated hand, forearm, battery, fan, sensing
Wrist wearable device	Jeong et al. [29], 2019	Active coiled SMA muscles	151 g	1.32 N·m flexion torque	2 DOF	NR	NR	Wearable wrist assist prototype
Elbow wearable device	Jeong et al. [32], 2024	Active pre-detwinned springs + coolant	NR	3.5 N·m torque	>60% contraction	0.5 Hz	Coolant used; electrical power/skin temperature NR	Wearable muscle module
Textile wearable glove	Lee & Park [31], 2024	Active knitted SMA	NR	Grip metric +55.01%	ROM +13.71%	NR	Skin temperature +2.21 °C	Human wearable rehabilitation test
Textile artificial muscle	Shin et al. [33], 2024	Active woven 2D zigzag SMA	7.5 g actuator	Lifted 2 kg; not a hand grip-force test	40% contraction	NR	NR	Actuator/textile demonstration
Passive superelastic structure	Lee et al. [20], 2026	Passive superelastic Nitinol skeleton; no thermal actuation	NR	>2× payload capacity versus rigid-palm comparator	Deformation up to 28%	Not applicable	No Joule heating	Contextual structural evidence only; excluded from thermal-actuation conclusions

2.4 Hybrid Architecture as a Near-Term Route

The short-term case for hybridization is based on function partitioning, not on simply adding a motor to an SMA actuator. A high-bandwidth motor or tendon drive should perform frequent opening and closing; SMA should be reserved for infrequent posture change, compact release, or stiffness switching. A latch or non-backdrivable element should maintain static grip without continuous heating, and passive compliance should absorb contact shocks. Existing motor-SMA fingers, SMA wrist modules, self-locking grippers, and Nitinol-supported hands illustrate elements of this approach [17-20,23].

A defensible hybrid design should satisfy several rules: define the SMA maximum on-time and required cooling interval; report all body-worn auxiliary mass and volume; guarantee a safe power-loss and manual-release state. Without this accounting, hybridization merely moves the thermal and maintenance burden elsewhere in the prosthesis.

3. Challenges of SMA-driven Prosthetic Systems

3.1 Performance Trade-offs

SMA actuators are compact, quiet, and capable of muscle-like contraction, but these advantages do not make them suitable for every upper-limb prosthetic task. One of the main design trade-offs is between output capacity and packaging size. Increasing the wire diameter or using parallel SMA strands can increase the available force, but it also raises the current demand, thermal inertia, and cooling load. Coiled SMA springs provide a larger stroke than straight wires, although their stiffness and output depend strongly on coil geometry, preload, and operating conditions. They can therefore be used in appropriately designed low-load or intermittent joint mechanisms, whereas higher-load applications may require additional transmission, guidance, or structural reinforcement.

This trade-off also explains why comparisons based only on SMA wire diameter, material mass, or isolated actuator output may overestimate the benefit obtained in a wearable system. In this review, system-level output is evaluated by relating the measured gripping force or joint torque to the total wearable volume required to produce that output. The wearable volume includes not only the SMA element, but also the transmission, driver electronics, sensors, cooling components, thermal insulation, housing, connectors, and the portion of the battery assigned to the corresponding function. Any off-body power supply, pump, or control equipment should be reported separately. Because gripping force and joint torque represent different prosthetic functions, they should be reported as separate indicators rather than combined into a single ranking. When the original study does not provide sufficient information about the output measurement or the complete system boundary, no normalized value should be calculated, and the corresponding entry should be marked as not reported.

A second trade-off concerns response time and energy consumption. Increasing the input current can shorten the heating stage, while thinner SMA elements or active cooling can accelerate actuator reset. However, these approaches do not eliminate the required heating–cooling cycle and may introduce additional power consumption, heat flux, noise, weight, or maintenance requirements. Similarly, coiled geometries and compliant transmissions can increase motion range but also make the system more sensitive to preload, geometric parameters, and lateral instability. Response speed should therefore be evaluated together with cycle energy, temperature rise, applied load, and sustainable duty cycle rather than treated as an independent performance indicator.

Continuous grip imposes another problem for SMA systems. Most prosthetic functions need to close the fingers and hold objects steadily. Continuous thermal excitation in the holding stage is not feasible and carries a thermal risk. Mechanical latches, brakes, non-backdrivable transmissions, passive elastic balancing and multistable structures reduce continuous SMA activation and significantly lower the total power consumption during full-grasping cycles [19]. Therefore, the full range of the operating cycle (including closing, contact, holding, transport and releasing) should be used to evaluate energy efficiency rather than just one or two isolated contraction tests.

Cyclic fatigue limits the operating range of SMA. High transformation stress and large strain increase the single-cycle work output but also accelerate functional degradation, such as stroke attenuation, force decay, shifted transformation temperatures, resistance drift and eventually fracture [36]. A lower stress threshold, a reduced strain range, smooth-wire terminals, and a controlled peak temperature all extend the service life but reduce the available actuation output. SMA performance should thus be characterized by the coupled force-stroke-response-temperature-lifetime relationship, rather than isolated peak force or maximum contraction values.

Task-dependent priorities for actuator speed. Prosthetic hands need fast pre-shaping before contacting an object, and stable holding force, a low-temperature surface, and secure retention are the main goals after grasping. Wrist adjustment modules operate infrequently but need to resist external moments to maintain a fixed position. Thumb positioning units have a demand for high pose repeatability; otherwise, the range of grasp modes will be very small. The selection of SMA is based on the required function and application environment of a prosthesis, not a single speed standard. The mechanical compliance and positioning accuracy need to be further reconciled. Compliant SMA-driven fingers have a slight joint-angle deviation and thus improve object adaptability and grasping stability. Small angular deviations at the wrist result in disalignment of the tool and consequently increased shoulder movement. Therefore, the evaluation indices should separate the accuracy of unloaded position, stability of loaded orientation, control of contact force, grasp success rate, release reliability and end-user task performance; soft adaptive fingers and wrist tuning mechanisms should not use the same assessment standards.

Biomimetic design has slight trade-offs. SMA bundles, coiled artificial muscles and textile actuators all have the geometry and soft-contraction properties of biological muscles. Natural muscles have an inherent distributed sensing function, blood supply, self-repair, high-efficiency biochemical energy conversion, etc., and cannot be replicated by SMA hardware. Biomimetic design is only useful in engineering if it can reduce the distal mass, improve human safety, simplify control logic or enhance grasping adaptability; pure visual resemblance has no functional advantage.

The lightweight design must also have a thermal and mechanical defence. Thin-walled and sparsely insulated shells have a low overall weight but are exposed to high temperatures and may be damaged by abrasion or overload on the SMA strands. Heat spreaders and shielding covers improve thermal safety but increase the mass and expanded heated area of the prosthesis. Redundant SMA wires improve fault tolerance but are more power-hungry and complex to assemble at the terminals. Therefore, the lightest laboratory prototype is not necessarily a clinically viable device. A typical SMA prosthetic system should have a relatively small distal weight, be easy to use, have good wear resistance.

3.2 Engineering Challenges

The main engineering bottlenecks are nonlinear dynamics and state unobservability of SMA actuation. Many factors that affect the performance of SMA are related to electricity, heat, mechanics, resistance, temperature, phase fraction, stress and strain, external loads. Multiple control schemes such as differential hysteresis modeling, antagonistic trajectory tracking, co-contraction regulation and resistance-based feedback have been proposed to boost actuation precision [37-40]. Advanced algorithms including inverse hysteresis compensation, adaptive control, Kalman filtering, minor-loop modeling, recurrent neural networks, particle filtering and LSTM self-sensing further enhance state prediction and cut sensor count [41-50]. Even so, these approaches cannot eliminate mandatory thermal limit supervision and periodic recalibration after component aging, repair or SMA replacement.

Self-sensing stands out for miniaturized prosthetic hardware, as SMA strands simultaneously function as actuators and displacement sensors. Variations in electrical resistance reflect phase transition, temperature shift and deformation, which reduces reliance on extra position transducers [46,51]. Nevertheless, the resistance-displacement correlation is nonstationary, fluctuating with preload, ambient heat dissipation, minor hysteresis loops, accumulated fatigue, external contact and modular replacement. Accordingly, self-sensing calibration must be conducted under realistic loading and partial excitation cycles, instead of ideal full heating-cooling cycles only. The control system of the service-oriented prosthesis needs to identify swapped SMA units, confirm their dynamic response, and limit the output until correct calibration is performed.

The other is the problem of thermal safety. A single point of temperature measurement cannot cover the local hot spots around crimp joints, welds, bent sections and poor heat dissipation areas, and the temperature of the outer casing is too slow to protect both the actuator and human users. Resistance-based thermal estimation has a small layout but is affected by phase transformation and mechanical strain. A strong prosthetic framework is employed for voltage/current measurement, thermal numerical modeling, distributed physical thermometers and independent hardware overcurrent cutoff. The controller will reduce the output force, motion speed or duty cycle automatically when the thermal safety margin is reduced, and switch to a pre-set safe mode after an inconsistency between sensor readings and model predictions has occurred.

Long-term stability is a reason for not having commercialised it clinically. SMA functional degradation occurs before complete wire fracture and is manifested by stroke attenuation, an inability to reset, resistance drift, and shifted transformation temperatures. Material heat treatment optimisation and fatigue prediction models extend service life[52,53], and high-speed antagonistic layouts plus active/passive heat dissipation solutions expand operating bandwidth [54,55]. However, standardised prosthetic validation should also include mixed cyclic loads, sustained holding, accidental overload, humid and sweaty environments. Daily wearable operation differs significantly from continuous-amplitude cyclic laboratory tests

Manufacturing inconsistency reduces experiment replicability. All of them are prone to the same two problems: changes in SMA phase transition characteristics and fatigue endurance. Bundled SMA wires are subject to non-uniform load and heat distribution, and small resistance differences can cause asynchronous activation. Strict quality control criteria need to specify alloy grade, trained dimensions, reference-temperature resistance, transformation interval, strain-dependent output force and terminal tensile strength. Modularity of actuators will improve maintainability only if the replacement units support uniform pre-tensioning installation, stable electrical connection and consistent calibration workflows.

Wearable integration shows that lab prototypes are far from market-ready prosthetic devices. High-stroke wearable SMA actuators, triple hybrid motor-SMA-electromagnet hands, compact SMA locking brakes and reservoir self-sensing modules provide the basic technical component [51,56-58]. Functional upper-limb prostheses also have high-current drive electronics, matched battery capacity, thermal-insulated shells that do not accumulate heat, durable connectors, real-time surface temperature monitoring, safe power-loss behaviour, manual release mechanisms and standardised recalibration workflows. The omission of the auxiliary system will reduce the high-compactness benefit of SMA significantly.

Failure mode analysis must be embedded in the early architecture design phase. A single broken SMA wire will immediately stop output; however, multi-strand bundles can share the load and continue to operate partially after damage. Spring-biased actuators return to a fixed open/neutral state after a power failure, and antagonistic SMA pairs may stop at an unknown equilibrium as both strands cool. Self-locking hybrid structures can hold the clamp without power and require separate manual release logic. Different tasks have different ideal failure states: automatic hand opening may drop an object, and permanent closure could trap the user or prevent prosthesis detachment. Safe shutdown logic, emergency release and obstacle response should be regarded as core design requirements rather than after-the-fact additions.

3.3 Hysteresis Models, Reduced-order Models, and Control Strategies

SMA models can be organized by the information they preserve and the computational burden they impose. The Liang–Rogers one-dimensional constitutive model links stress, strain, temperature, and martensite fraction and provides a physically interpretable basis for shape-memory and pseudoelastic behavior [58,59]. The Brinson formulation extends this family by separating stress-induced and temperature-induced martensite and allowing non-constant material functions [60]. These models are useful for design and extrapolation across load and temperature, but they require material identification and a coupled thermal model; parameter drift after training or fatigue can reduce accuracy.

Input-output hysteresis models instead identify the path-dependent mapping without resolving every internal phase variable. Preisach models represent hysteresis as a weighted population of relay operators and can reproduce major and minor loops [61]. Duhem models use differential loading and unloading laws; with suitable slope functions they can represent saturation and minor loops and can be inverted for feedforward compensation [62]. These models are attractive for embedded control but must be reidentified when load, cooling, aging, or actuator replacement changes the input–output map.

Full actuator-system models couple Joule heating, convective cooling, phase evolution, constitutive behavior, and joint mechanics. They support nonlinear control and state estimation but can be too high order or numerically stiff for a multi-DOF wearable controller [63,64]. Reduced-order models retain the dominant joint dynamics and represent omitted SMA physics and uncertainty through an online estimated perturbation. Shahir et al. used this approach to design an input-saturation-aware position controller, reducing the state dimension while updating the model from measured data [65]. The benefit is real-time feasibility; the limitation is that stability and prediction remain tied to the validated operating envelope and the quality of the estimator.

Control architectures should therefore be layered. An inner current loop enforces electrical limits; a model-based or data-assisted estimator reconstructs temperature, hysteresis state, or lumped disturbance; an outer position/force loop uses inverse compensation, feedback linearization, sliding-mode, adaptive, or model-free control; and an independent supervisor enforces temperature, on-time, cooling, and fault limits. Extended-state-observer feedback linearization has been validated experimentally for SMA actuation [66], and observer-based fault-tolerant control has used estimated perturbations to detect faults and reconfigure a reduced-order controller [67]. These methods improve tracking and resilience but do not eliminate cooling time, energy demand, fatigue, or the need for a safe mechanical release. Table 2 consolidates the principal failure mechanisms, corresponding mitigation strategies, unavoidable penalties, and minimum verification evidence[8,9,35-67].

Table 2. Challenge–mitigation framework for thermally activated SMA prosthetic systems.

Challenge / mechanism	System consequence	Improvement strategies	Added penalty or limitation	Minimum verification evidence
Cooling-limited bandwidth and heat accumulation	Slow reset, falling force, unsafe casing or socket temperature	Thin/distributed wires; forced air or liquid cooling; heat spreaders; duty limits; latches; motor-SMA function partitioning	Fan/pump noise, mass, volume, power, sealing, and maintenance	Heating and cooling time; full grasp-cycle energy; hotspot and skin/socket temperature; declared duty cycle
Thermal hysteresis and minor-loop dependence	Position/force error during partial activation and interrupted grasping	Liang/Brinson constitutive models; Preisach or Duhem inverse compensation; observer-based feedback; load-aware calibration	Identification effort, computation, sensitivity to load/ambient changes	Major and minor loops under multiple loads and ambient temperatures; tracking error after partial cycles
Fatigue and terminal damage	Stroke/force loss, resistance drift, incomplete reset, eventual fracture	Limit transformation strain/stress/peak temperature; smooth crimps; preconditioning; redundant strands; replaceable modules	Reduced peak work; more parts; replacement and recalibration burden	Mixed-amplitude cycling; sustained hold; overload; failure distribution; retained stroke/force/resistance
Self-sensing and parameter drift	Incorrect state estimate after aging, cooling changes, contact, or replacement	Resistance plus current/temperature fusion; Kalman/particle/RNN/LSTM estimators; module identification; periodic recalibration	Additional sensors or computation; model mismatch remains possible	Calibration across loads, partial loops, ambient states, aging stages, and replaced modules
Static holding energy and unsafe failure state	Continuous heating, object drop, trapping, or unknown antagonistic equilibrium	Mechanical latch/brake; non-backdrivable transmission; passive balance; defined power-loss state	Interfaces, backlash, extra mass, separate release logic	Closing-contact-hold-transport-release energy; power-loss test; blocked-motion and emergency-release tests

4. Comparison with other Actuation Technologies

The performance of SMA actuators should be compared with that of other widely used or studied driving schemes for upper-limb prostheses. Motor-driven actuation is a relatively mature solution for cyclic grasping; it has continuous rotation, a broad bandwidth, a complete control system, and simple-to-use position sensing. Nevertheless, motors that are equipped with gearboxes, bearings, encoders and transmission linkages have relatively large internal dimensions and added distal mass and acoustic noise [2]. Compared with motorised structures, SMA modules have relatively small active sections, flexible wiring and are naturally quiet. However, due to the impact of thermal excitation on the circuit, insulation and heat-dissipating parts, dynamic response and energy efficiency decline. Fair cross-technology evaluation needs to use all-device metrics, such as total mass, output capacity, duty cycle, thermal safety and task-based energy consumption, rather than just material-only power density.

Pneumatic artificial muscles and fluidic soft actuators are another group for comparison, and they have large-deformation, high-compliance features that are suitable for soft robotic hands and wearable rehabilitation aids. Passive soft hand design reduces control by using natural body dynamics and mechanical adaptability [68]. Pneumatic systems need auxiliary pumps, pressure valves, tubing, sealing devices and leak control, and are thus not very portable or simple to maintain. Existing reviews show that pressure regulation has problems of persistence and hysteresis characteristics in portable pneumatic actuators [69]. SMA does not require an external pressure source, but it is affected by thermal response and has relatively low energy efficiency.

The third benchmark group is the series-elastic (SEA) and variable-impedance (VSA) motor system. Such schemes are based on standard motors and add elastic components to improve force regulation and shock resistance, thus combining mature electromechanical drive with tunable compliance [70]. Unfortunately, extra elastic structures, additional sensors and extended transmission chains all increase the total volume and mechanical complexity. SMA materials can be self-compacting without external spring elements, but they exhibit thermal hysteresis and slow heat dissipation; thus, high-bandwidth and high-precision impedance modulation is challenging.

No single drive technology can meet all the demands for upper-limb prostheses universally, as shown in the above comparisons. Motorised systems are suitable for high-frequency, high-precision continuous movement; pneumatic fluidic actuators can be chosen if large-deformation and safe-contact-compliance offsetting of the external pressure equipment are needed; SEA/VSA motors are suitable for scenarios requiring accurate force control and adjustable stiffness. SMA actuators have certain advantages for compact, quiet, intermittent applications, such as thin finger segments, thumb pose adjustment, miniature release locks, low-cycle wrist fine-tuning, superelastic flexible frameworks, and wearable artificial muscles with a relatively large heat dissipation area. The applications serve as the main basis for selecting actuators. Multi-degree-of-freedom prosthetic hands for daily life have relatively mature, high-response, and reversible motor drives. Soft prototype fingers and rehabilitation gloves can use pneumatic solutions for better compliance, and wrist/elbow modules that require controllable impedance are generally selected from elastic-motor hybrid systems. SMA is only a feasible choice when there is infrequent movement, a small installation area, a requirement for low noise, or a sufficient heat dissipation area can be provided for the actuator.

A scenario-based approach is less likely to be overblown and also won't be discarded simply because it didn't meet all the joint-performance requirements. The technological level of the manufacturing supply chain and maintenance facilities affects it. Miniature motors, gearheads, encoders and drive boards are all standardised off-the-shelf components with complete qualification workflows. Although the mature valves and pressure transducers of pneumatic systems are well-known, lightweight portable pumps are still lacking [69]. SEA/VSA motors have the same conventional electromechanical hardware but require a complex spring design, sensing layout and multiple calibrations [70]. Although commercial NiTi SMA raw materials are accessible, actuator performance is highly sensitive to forming processes, shape training, terminal crimping, pre-tension and thermal treatment. Broad clinical deployment of SMA prosthetics requires standardized replaceable modules, traceable material batches, validated replacement workflows and universal design guidelines independent of specialized metallurgy expertise. Quantitative comparison must remain representative rather than universal because source boundaries differ. The motor benchmark in Table 3 is a prosthetic-hand design envelope, the pneumatic example includes both glove and belt-pack mass, the SEA example is an integrated hand exoskeleton, and the SMA entries distinguish a lightweight hand prototype from a highly integrated prosthesis [2,14,23,29,31-33,68-72]. These data reveal auxiliary-system penalties while avoiding conversion of payload, fingertip force, and joint torque into a false common quantity.

Table 3. Quantitative system-level benchmarks for upper-limb actuation technologies.

Technology / representative system	System boundary and mass	Output	Response / bandwidth	Electrical or fluid input	Thermal / duty evidence	Principal gain	Principal limitation
Thermal SMA: 3D-printed hand [14]; 19-DOF prosthetic hand [23]; wrist assist [29]	235 g hand [14]; 370 g complete prosthesis, including forearm hardware [23]; 151 g wrist device [29]	133 g payload [14]; 2.5 kg reported maximum load [23]; 1.32 N·m wrist flexion [29]	0.125 Hz [14]; ~1.3 s command-to-activation [23]	7.82 W for 3D-printed hand [14]; other integrated power NR	Socket interior 27.2 °C after 30 min [23]; knitted glove skin rise +2.21 °C [31]; full daily duty largely NR	Compact routing, quiet operation, high DOF at low hand mass	Cooling, hysteresis, power, fatigue, and incomplete reporting of duty/battery energy
Motor + gearbox: prosthetic-hand benchmark [2]	Recommended complete hand mass <500 g, including electronics/glove	Recommended minimum grip force of 45 N	0.8–1.5 s closing considered adequate	Power varies by motor/gearbox and task; not pooled in source	>500,000 grasp cycles between routine service suggested; thermal rise NR	Mature sensing/control and repeated multifunction grasping	Distal mass, gear volume/noise, transmission wear
Pneumatic/fluidic: portable soft glove [71]	285 g glove + approximately 3.3 kg belt-mounted power/control unit	Up to 8 N fingertip force at 345 kPa	Cycle/step time NR in cited report	Hydraulic/pneumatic pressure source at 345 kPa; electrical energy NR	No actuator heat at hand; operating duration NR	Large deformation and contact compliance	Off-hand pump/valve/tubing mass, leakage, pressure-source burden
SEA motor system: HandeXos-β hand exoskeleton [72]	Integrated index–thumb exoskeleton; total mass/power NR	Approximately 4 N fingertip force	~0.3 s position/torque step response; −3 dB cut-off frequencies ranging from approximately 2.5 to 4 Hz	Motor/driver input power NR	Thermal/duty data NR	Direct torque sensing, controllable impedance, shock tolerance	Added spring/sensor/transmission volume; bandwidth–stiffness trade-off

5. Conclusion

SMA actuators constitute a promising compact, low-weight, silent and compliant driving solution for targeted upper-limb prosthetic tasks. Four mainstream SMA layouts deliver differentiated merits: straight wires realize dense wiring layout and high tensile force; coiled springs extend actuation stroke; antagonistic architectures achieve bidirectional movement and adjustable preload; hybrid schemes cut SMA thermal load by transferring cyclic motion, static holding and stiffness tuning to auxiliary mechanisms. A wide range of prototype prosthetic hands, wearable aids and biomimetic devices verify SMA's capacity to produce effective force and motion within confined cavities. Nevertheless, its clinical translation is hindered by sluggish heat dissipation, thermal hysteresis, narrow operating bandwidth, cyclic fatigue, strict thermal safety constraints and complicated real-time state observation.

The most credible near-term applications are intermittent digit or thumb motion, low-cycle wrist adjustment, compact locking/release, and passive superelastic support. High-frequency grasping, sustained torque, and high-bandwidth impedance control remain better matched to motors, pneumatic systems, or elastic motor architectures, depending on the task. Function-partitioned hybrids are promising only when their complete body-worn mass, volume, power, thermal behavior, serviceability, and failure state are demonstrated.

Future research will build a full research chain covering material characterization and clinical verification at the end-user level. The standardisation of reports should cover alloy properties, terminal processing conditions, coupled force-stroke-temperature characteristics, resistance drift, joint torque and bandwidth, full-device mass and power consumption, surface temperature under cosmetic sleeves, failure modes, and human-centered task performance. Combine multi-scale test data to help identify the root cause of performance bottlenecks and determine whether the limitations are due to inherent properties of SMA, transmission layout, control algorithms, thermal management or human-prosthesis interaction.

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Not applicable. This study is a review of previously published literature and did not involve human participants, animals, biological materials, or personally identifiable data.

Informed Consent

Not applicable.

Data Availability Statement

This review is based entirely on previously published studies cited in the manuscript. No new datasets were generated during the present study.

Author Contributions

Zheng Deng conducted the literature search, screening, and analysis and prepared the original draft of the manuscript. Tian Yang critically reviewed the manuscript and contributed to language editing. Qiaoling Meng contributed to the development of the review methodology and the critical revision of the manuscript. Hongliu Yu supervised the work and coordinated the overall manuscript review and revision process. All authors read and approved the final version of the manuscript.

Conflict of Interest

The authors declare no conflict of interest.

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