



W-DFAS rehabilitation Glove: Design and experimental Validation

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ABSTRACT

Shape Memory Alloy (SMA) actuators are attractive for wearable hand rehabilitation due to their high power-to-weight ratio, silent operation, and muscle-like contraction behavior; however, their limited stroke and slow thermal recovery restrict multi-finger actuation in compact gloves. Differential mechanisms that enable one actuator to drive multiple fingers are common in motor-driven hands but remain rare in SMA-based wearable gloves due to force sharing, thermal, and spatial constraints. This study presents a Wearable Dual-Finger Actuation System (W-DFAS) integrating DFAM_6X stroke amplification, a double U-shaped parallel SMA layout, and a hybrid recovery approach combining elastic elements, a passive spring, and PWM-controlled forced-air cooling. Under PWM control at 2.2 A for 1 s, the glove achieved maximum flexion with coordinated MCP–PIP–DIP bending across all four fingers, and total bending angles exceeded 200° for the index/middle and 190° for the ring/little. DFAM transmission analysis showed a fixed experimental gain of 3.19X, reducing required actuator stroke by 68.7% and enabling full-range postures with short SMA strokes (e.g., 12.0 mm at 100% PWM), while reducing required SMA length from ~ 958 mm (no DFAM) to 300 mm (with DFAM). Forced convection reduced extension recovery to ~ 7 s, enabling ~ 7 cycles/min for repetitive rehabilitation tasks. Grasping trials across cylindrical, spherical, box-shaped, and irregular objects demonstrated stable manipulation of ~ 20–400 g items, supporting ADL-oriented rehabilitation.

1. Introduction

Stroke remains one of the most significant global health challenges and a leading cause of long term disability worldwide [1]. In Malaysia alone, it is estimated that five individuals suffer a stroke every hour, underscoring the growing burden placed on the national healthcare system [2]. According to the World Health Organization (WHO), stroke is the second leading cause of death globally, affecting approximately 15 million people each year, of whom nearly 6 million die and about 5 million are left with permanent disabilities [3]. In Europe, stroke accounts for approximately 650,000 deaths annually, and more than two-

thirds of survivors require long term rehabilitation to regain motor function and independence [3].

Rehabilitation therefore plays a critical role in improving quality of life for stroke and injury patients by restoring physical function, autonomy, and participation in daily activities [3,4]. Upper limb rehabilitation focuses on recovering hand function, which is essential for performing activities of daily living. Robotic and wearable rehabilitation devices, especially hand rehabilitation gloves, have emerged as promising tools to support this process by enabling repetitive, controlled, and task specific exercises that promote neuroplasticity and motor recovery. These devices assist or replicate natural finger movements, facilitating

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fine motor rehabilitation while reducing therapist workload [5].

The effectiveness of rehabilitation gloves depends fundamentally on the performance of their actuation systems, which convert electrical or thermal energy into mechanical motion. Conventional actuators such as DC motors, servo motors, and stepper motors are widely used in robotic systems [6,7]; however, their application in wearable rehabilitation devices is limited by bulkiness, mechanical noise, low energy density, and rigid transmission structures [8–10]. Similarly, pneumatic and hydraulic actuators offer compliance and adaptability but require auxiliary components such as compressors, pumps, and valves, resulting in increased system weight, complexity, and reduced portability [11,12].

Advances in materials science have introduced smart actuators capable of overcoming many of these limitations. Intelligent materials—including ionic polymer–metal composites (IPMCs), dielectric elastomers (DEAs), piezoelectric polymers (PEPs), and shape memory alloys (SMAs) have enabled the development of compact, lightweight, and compliant actuation systems suitable for wearable robotics [8,10,13–16]. Among these, SMAs have attracted particular attention due to their unique ability to recover a predefined shape upon heating, high power-to-weight ratio, silent operation, corrosion resistance, and favorable fatigue characteristics [17,18].

Shape memory alloys are increasingly preferred over traditional electric, pneumatic, and hydraulic actuators because of their low volume, high energy density, flexibility, noiseless operation, and simple mechanical structure [19–23]. SMA actuators are capable of generating contraction forces up to 400 times greater than magnetic actuators and 150 times greater than hydraulic actuators of equal volume, while maintaining compact size and minimal acoustic disturbance [8]. These characteristics make SMA wires particularly suitable for biomedical, robotic, automotive, and aerospace applications [10,19,24–26]. In rehabilitation gloves, SMA wires enable human friendly, compliant actuation that enhances comfort, safety, and wearability for stroke and hand injury patients [27–30].

Despite their advantages, the integration of SMA actuators into wearable rehabilitation gloves presents several challenges. SMA wires exhibit limited recoverable strain (typically 3–5%), relatively slow cooling and recovery times, and difficulties in achieving both high displacement and sufficient fingertip force simultaneously [10]. To compensate for these limitations, many existing designs employ long SMA wires routed through multiple pulleys, Bowden cables, or displacement extending mechanisms [23,29,31]. While these approaches increase motion range, they also introduce higher friction, increased mechanical complexity, greater energy consumption, and added system weight. Force enhancement strategies such as wire bundling, hybrid SMA muscles, and elastic compensation further increase structural bulk and mechanical losses, limiting suitability for compact wearable systems [32].

Over the past decade, numerous robotic gloves and hand exoskeletons have been proposed using diverse actuation principles, including soft pneumatic actuators, tendon-driven systems, motorized exoskeletons, and SMA-based mechanisms [31,33–43]. These systems vary significantly in terms of motion range, force output, actuation speed, cooling requirements, and user comfort.

Comparative analysis of these robotic gloves reveals persistent limitations across existing designs. Soft pneumatic gloves provide safe and compliant interaction but depend on bulky external air supply systems, restricting portability. Motorized and tendondriven gloves offer higher force output and precise control but suffer from increased weight, mechanical complexity, and reduced comfort. SMA-based gloves achieve compactness and silent operation but frequently exhibit limited bending angles, insufficient force amplification, slow actuation–relaxation cycles, thermal accumulation, and poor finger independence. Many reported systems lack integrated cooling solutions or demonstrate flexion–extension frequencies unsuitable for real-time rehabilitation tasks.

Another critical limitation in current SMA-driven gloves is the

predominance of one actuator per finger architecture. Although straightforward to implement, this configuration restricts coordinated multi-finger motion, prevents adaptive grasping, and results in uneven force distribution when interacting with objects of varying geometry [7–9]. In contrast, differential mechanisms enabling a single actuator to drive multiple fingers have been widely explored in DC motor driven systems. Belter and Dollar (2013) introduced an underactuated prosthetic hand using a pulley-based differential to enable grasp type switching with a single motor [1]. Xu et al. developed the Exo-Glove employing a whiffletree-type differential to flex two fingers from one motor [2], while Dragusanu et al. proposed a gear-based differential exoskeleton coupling adjacent fingers to reduce complexity [3]. Jeon et al. further demonstrated adaptive multi-finger grasping using a magnetic-gear belt-driven differential mechanism [4].

While differential driven multi-finger actuation is well established in motor driven systems, its implementation in SMA-based wearable gloves remains extremely rare. The primary barriers include force-sharing inefficiencies, thermal constraints, and spatial limitations associated with wearable designs. In wearable robotic hands, all transmission and actuation components must be located externally, as the human hand occupies the internal space, making integration of conventional differential mechanisms particularly challenging [6].

To address these unresolved challenges, this study proposes a novel Wearable Dual-Finger Actuation System (W-DFAS) that integrates a Dual Finger Amplification Module (DFAM) with SMA-based actuation. The proposed system introduces four key innovations: (1) a DFAM-6X mechanism to amplify SMA displacement without long-wire routing or bulky extenders; (2) a double U-shaped parallel SMA configuration to enhance force output while maintaining acceptable thermal cycle time; (3) a hybrid recovery strategy combining PWM-controlled forced air cooling, elastic rubber bands, and a passive spring to accelerate relaxation; and (4) a compact differential architecture enabling a single SMA actuator to drive two fingers simultaneously with adaptive force sharing.

To the best of our knowledge, no prior study has integrated a dual finger amplification system combined with a differential mechanism into an SMA-actuated wearable rehabilitation glove. By addressing the limitations of displacement, force generation, cooling efficiency, and coordinated multi finger motion, the proposed W-DFAS aims to provide a lightweight, thermally efficient, and mechanically simplified solution for functional hand rehabilitation.

Compared with many previously reported SMA-based rehabilitation gloves and smart grippers, the proposed W-DFAS offers several distinct design advantages. First, unlike conventional one-actuator per finger SMA gloves, the present system employs a dual-finger differential actuation architecture that enables one actuation module to drive two fingers simultaneously, thereby reducing structural complexity while preserving coordinated motion. Second, the DFAM-based mechanism provides displacement amplification without requiring excessively long SMA routes, improving compactness and wearability. Third, the double U-shaped SMA configuration enhances force generation within a constrained layout, while the hybrid recovery strategy combining elastic elements, a passive spring, and forced air cooling improves extension recovery and supports repetitive operation. This approach also eliminates the need for antagonistic SMA actuation during extension, thereby reducing power consumption, simplifying the actuation scheme, and avoiding additional actuator weight.

2. Tendon Displacement–Joint angle relationship

Each finger in the hand comprises multiple phalanges and is conceptualized as a serial open kinematic chain. As illustrated in Fig. 1, the index finger, consisting of various bones and joints, functions as a three revolute joint robotic manipulator. Each finger includes three principal joints: the metacarpophalangeal (MCP), proximal interphalangeal (PIP), and distal interphalangeal (DIP) joints [31,34]. Muscles in

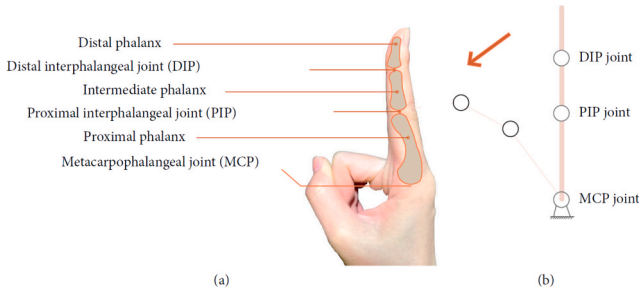


Fig. 1. Theoretical Model: (a) Identification of Finger Joints; (b) Streamlined Model [31].

the human hand are the power behind hand movement [31]. In robotic hand, these joints are controlled by tendons attached to actuators. In our case, shape memory alloys (SMAs) wire change the length of the tendons and thereby adjust the joint angles. Shape Memory Alloys (SMAs), known for their shape memory effect, are extensively utilized as artificial muscle actuators in bionic devices. When heated, SMA wires undergo phase transformation and shorten, mimicking the function of human muscles to enable finger flexion and extension [8]. The relationship between tendon displacement and joint angle, as depicted in Fig. 2.

To model the finger flexion mechanism, a two dimensional representation of the index finger was constructed along the sagittal plane. Each finger is represented as a three link serial kinematic chain, corresponding to the metacarpophalangeal (MCP), proximal interphalangeal (PIP), and distal interphalangeal (DIP) joints [29,31,34]. The tendon displacement required for flexion is obtained from the joint angles using the following equation:

$$x = l_1 \sin\left(\frac{\theta_1}{2}\right) + l_2 \sin\left(\frac{\theta_2}{2}\right) + l_3 \sin\left(\frac{\theta_3}{2}\right) \quad (1)$$

where x represents the tendon displacement (mm), l_1 , l_2 , and l_3 are the thickness of the MCP, PIP, and DIP joints (mm), respectively. θ_1 , θ_2 , and θ_3 are the joint angles ($^\circ$) of MCP, PIP, and DIP joints, respectively. This expression is derived from the symmetric tendon deflection geometry at each joint. Compared to alternative formulations using half thickness parameters, this form avoids the inclusion of an additional scaling factor and ensures direct consistency with the experimentally measured joint dimensions listed in Table 2. Dividing the (x) obtained above by the strain rate can get the theoretical length of SMA wires [31,34]. lists the

measured knuckle thickness values (MCP, PIP, and DIP joints) of the index finger for wooden hand model (WHM) used in this study. These dimensions formed the basis for the tendon displacement and SMA wire length calculations [29,31].

Table 1 shows the variation range for each joint angle. Using this data, we can compute the maximum change in tendon length. Additionally,

Table 2 lists the measured knuckle thickness values (MCP, PIP, and DIP joints) for the wooden hand model (WHM) used in this study. These dimensions formed the basis for the tendon displacement and SMA wire length calculations.

Table lists the measured knuckle thickness values at the MCP, PIP, and DIP joints of the index finger for the corresponding measurements of the wooden hand model (WHM) used in this study. These anatomical dimensions served as the foundation for calculating the required tendon displacements and determining the appropriate SMA wire lengths for the proposed actuation system.

Table and.

Table 2, the maximum change in tendon length for the index finger can be determined. The Detailed Calculation Procedure.

From Table 1, the joint angles are: $\theta_1 = 85^\circ$, $\theta_2 = 100^\circ$, $\theta_3 = 80^\circ$. From.

Table 2, for: $l_1 = 24 \text{ mm}$, $l_2 = 22 \text{ mm}$, $l_3 = 20 \text{ mm}$

$$x_{\max} = 24 \sin(42.5) + 22 \sin(50) + 20 \sin(40)$$

$$x_{\max} = 24(0.6760) + 22(0.7660) + 20(0.6428)$$

$$x_{\max} = 45.92 \text{ mm.}$$

Given that shape memory alloys (SMAs) can generate a strain of 3–5%, a 4.5% strain has been selected.

$$L_{\text{SMA}} = \frac{x_{\max}}{\text{strain}} \quad (2)$$

$$L_{\text{SMA}} = 45.92 / 0.045 = 1020.51 \text{ mm}$$

This is the total SMA wire length required to achieve full finger closure for index at 4.5% strain.

The maximum tendon displacement ($x_{\max}$) was calculated for index

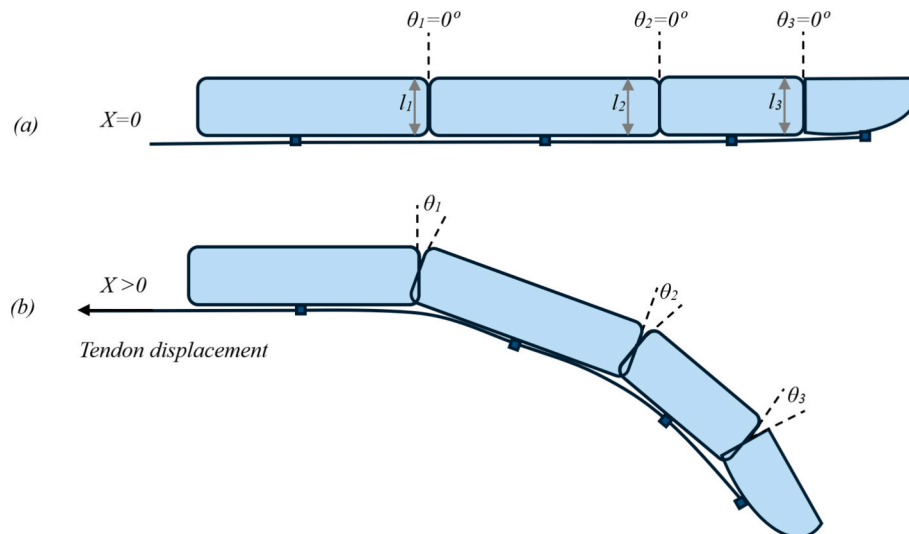


Fig. 2. Correlation between tendon displacement and joint angle: (a) extended tendon and (b) tensioned tendon [29,31].

Table 2

The thickness of knuckles of an index finger.

Interphalangeal	Index Finger	MCP	PIP	DIP	Ref.
Thickness (mm)	IF-WHM	24	22	20	[44]
MCP: Metacarpophalangeal; PIP proximal interphalangeal; DIP: distal interphalangeal					

finger dataset (IF-WHM) using Equation (1). The corresponding required SMA wire lengths L_{SMA} were then determined for three selected design strain values (4%, 4.5%, and 5%) based on Equation (1), as presented in Table 3.

3. Design of the wearable dual finger actuation system (W-DFAS)

Based on the WHM anthropometry ($x_{max} = 45.92$ mm) and a design strain of 4.5%, the required theoretical SMA length for our application is $L_{SMA} = 1020.51$ mm per tendon pathway. To accommodate the required SMA wire length within a compact and wearable configuration, a Dual Finger Amplification Module (DFAM-6X) was developed. This approach simplifies the system architecture while improving its capability to handle objects of diverse shapes and sizes. DFAM-6X integrates three fixed pulleys and four free pulleys to achieve a sixfold amplification of the SMA stroke. Such amplification ensures sufficient tendon displacement to generate the desired joint rotations and range of motion (ROM), thereby fulfilling the functional requirements of practical rehabilitation tasks while preserving a lightweight, wearable form factor. A key innovation in the proposed design is the incorporation of a conventional differential mechanism within a single module to actuate two fingers simultaneously. This approach reduces the total required SMA wire length by enabling two actuators to serve dual outputs. While the use of a differential mechanism increases stroke, it inherently reduces force on the opposing side. To address this limitation, two U-shaped SMA actuators, each with a diameter of 0.380 mm, were employed. This configuration doubles the available force output to approximately 45 N per actuator, yielding an estimated fingertip force of 8 N—sufficient for performing activities of daily living. The use of dual actuators also distributes the electrical load, which helps to reduce individual actuator heating and cooling cycles. In practice, experimental inaccuracies and frictional losses reduce the output force compared to theoretical predictions. Consequently, the use of two 0.380 mm diameter actuators ensures that the system maintains adequate force output to meet functional requirements despite these losses. All subsequent experimental investigations and numerical modeling in this study are based on this actuator specification. The detailed physical properties of the selected SMA wire are summarized in Table 4.

In the proposed design of the wearable Dual Finger Actuation System (W-DFAS), a fabric glove serves as the primary structural base, forming the interface between the actuators and the user's hand. The glove, made from cotton, enhances the stability of the wrist ligaments and tendons, thereby improving overall hand stability during device operation. Cotton is generally considered safe and non-allergenic for most users; however, the glove material can be substituted as needed to accommodate individuals with specific material sensitivities or allergies [31,34]. The Wearable Dual Finger Actuation System (W-DFAS) is a soft, wearable actuation platform designed to control the flexion and extension of two human fingers for assistive and rehabilitative applications. The system integrates multiple technologies to achieve lightweight, responsive, and compact performance suitable for wearable use. The W-DFAS architecture is organized into three primary units:

(a) the Actuation Unit, which generates finger flexion through the

Table 3

Maximum Tendon Displacement and SMA Wire Lengths at 4–5% Strain.

Dataset	x_{max}	L_{SMA} 4% (mm)	L_{SMA} 4.5% (mm)	L_{SMA} 5% (mm)
IF-WHM	45.92	1148.07	1020.51	918.46

Table 4

Thermal and electrical properties of the LT SMA wire [45].

Parameter	Description	Value	Unit
ρ	Density	6450	kg/m ³
d	Diameter	0.38	mm
l	Length	100	mm
T_m	Melting Point	1300	°C
ν	Poisson's ratio	0.33	—
α	Thermal Expansion Coefficient – Martensite	6.60x10 ⁻⁶	°C ⁻¹
	Thermal Expansion Coefficient – Austenite	11.0x10 ⁻⁶	°C ⁻¹
k	Thermal Conductivity	18	W/m·°C
ρ_r	Electrical Resistivity Martensite	8.00 × 10 ⁻⁷	Ω·m
	Electrical Resistivity Austenite	10.0 × 10 ⁻⁷	Ω·m
c_p	Specific heat capacity	837.36	J/kg·°C
h	Heat transfer coefficient	—	W/m ² ·°C
A_f	Austenite final temperature	78	°C
A_s	Austenite start temperature	68	°C
M_s	Martensite start temperature	52	°C
M_f	Martensite final temperature	42	°C

contraction of shape memory alloy (SMA) wires and a mechanical amplification mechanism called Dual Finger Amplification Module (DFAM). (b) the Passive Recovery Unit, which passively restores finger extension during the SMA cooling phase using tensioned elastic rubber bands and extension springs. This dual restoring mechanism ensures reliable and consistent finger return without requiring active antagonistic actuation. (c) the Support & Mounting Unit, which includes structural components such as PLA fingertip hooks, Velcro straps, and the glove base to ensure stability, correct alignment, and user comfort during operation. Fig. 3 shows the schematic diagram of the W-DFAM system.

(i) Actuation unit

The actuation unit of the W-DFAS glove is based on two U-shaped Shape Memory Alloy (SMA) wires integrated with the DFAM_6X module to achieve compact, amplified finger motion. Each SMA wire has a total length of 600 mm and is folded into a U-shaped configuration around dedicated routing holes in the DFAM, resulting in an effective working length of 300 mm per SMA strand. Electrical current supplied through terminal connections induces Joule heating, triggering SMA contraction and generating linear motion.

The SMA contraction force is transmitted via a lightweight polyethylene (PE) tendon line (0.5 mm diameter), which serves as the primary force transmission element between the actuator and the fingers. A fluorocarbon coated nylon monofilament tendon was selected due to its high tensile strength, abrasion resistance, low friction, and stable anti-curling behavior, ensuring consistent motion transmission in wearable conditions [46]. The tendon routing follows predefined anatomical pathways using custom 3D-printed PLA guides, PTFE tube segments, and tendon anchor guides (TAGs) positioned at the distal phalanx to maintain alignment and user comfort.

Because the intrinsic recoverable strain of SMA wires ($\approx 4\text{--}5\%$) limits direct displacement, the DFAM_6X module was introduced to mechanically amplify SMA contraction. The module employs a multi-pulley differential configuration that converts approximately 12 mm of SMA contraction into sufficient tendon displacement to achieve full MCP–PIP–DIP finger flexion. Initial PLA only prototypes exhibited excessive friction and reduced effective stroke. To address this, PTFE rods were integrated into both the sliding pulley and module base, forming low friction rolling interfaces that significantly reduced energy loss, improved durability, and enhanced transmission efficiency. The final DFAM_6X configuration provides a compact, lightweight, and

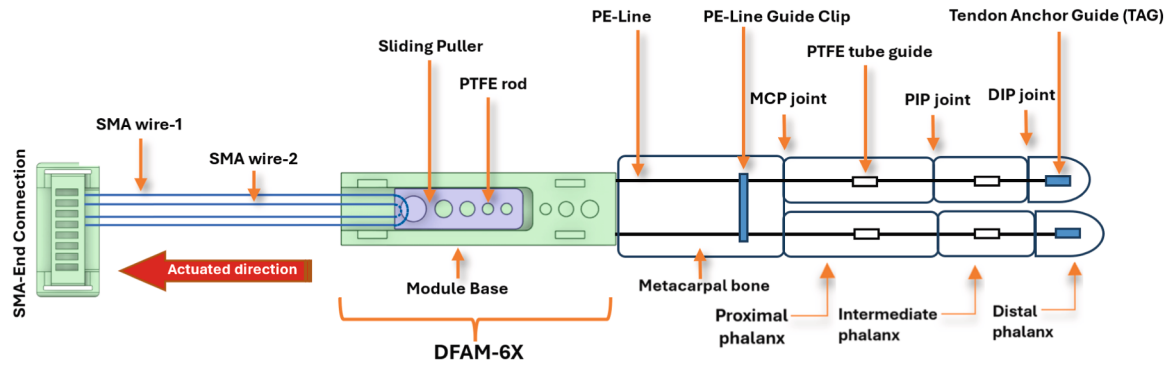


Fig. 3. Schematic diagram of the W-DFAS Glove at palm side.

thermally efficient actuation solution capable of delivering amplified displacement and reliable force transmission for wearable hand rehabilitation applications.

Fig. 4 illustrates the DFAM-6X module configuration, where Fig. 4 (a) presents the 3D assembly view highlighting the integration of the sliding puller, PTFE rods, module base, and PE-line pathway, while Fig. 4 (b) depicts the internal tendon routing scheme within the module. The routing layout ensures smooth force transmission by guiding the PE tendon along low-friction PTFE interfaces, enabling synchronized motion and efficient stroke amplification during SMA actuation.

(ii) Passive Recovery Unit

Robotic and prosthetic fingers actuated by one-way Shape Memory Alloy (SMA) wires require an external return mechanism to achieve finger re-extension after SMA-induced flexion. Previous studies have

implemented both passive and active recovery strategies. Passive approaches commonly employ mechanical springs or elastic elements that store energy during flexion and release it during extension, often referred to as bias or return mechanisms [35,40,43,47]. Alternative passive solutions include the use of superelastic SMA elements [39], while active approaches rely on antagonistic actuation using additional SMA wires or motors placed on opposing sides of the joint, increasing system complexity, weight, and power demand [29,31,41,48–51].

In the proposed W-DFAS glove, finger extension is achieved using a fully passive recovery strategy that combines elastic rubber bands and mechanical springs. The elastic rubber bands and extension spring were selected empirically through iterative testing to ensure reliable finger re-extension and stable recovery performance, rather than being explicitly characterized in terms of stiffness. Elastic rubber bands (ERB) are anchored to custom 3D-printed PLA hooks mounted along the dorsal side of each finger segment, providing a restoring force that returns the

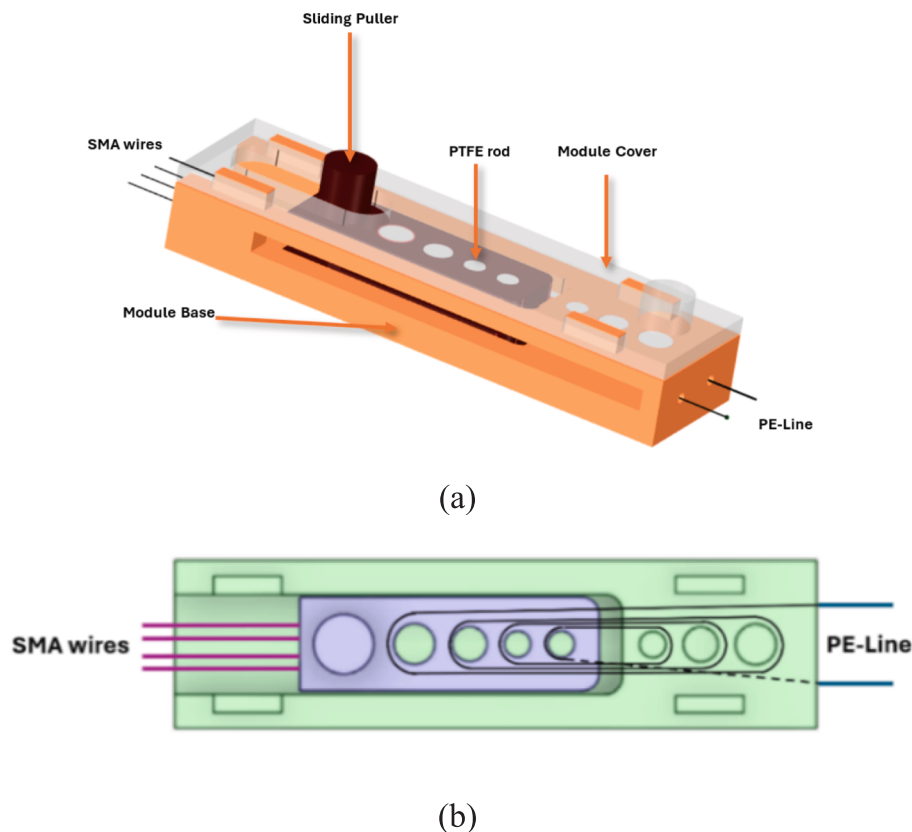


Fig. 4. DFAM-6X Module: (a) 3D Assembly View and (b) Internal Tendon Routing Configuration.

fingers to their neutral position once the SMA wires cool and relax. This elastic-based return mechanism is lightweight, compact, cost-effective, and does not require any external power source, thereby reducing overall energy consumption while maintaining reliable finger posture during non-actuation phases [43,52].

To ensure stable anchoring and effective force transmission, a Knuckle–Wrist Anchor (KWA) is employed to connect the proximal finger hooks to the dorsal side of the hand. Positioned over the metacarpal region and secured using a wrist strap, the KWA provides a robust mechanical interface between the finger return elements and the wrist, optimizing tendon routing and improving overall system stability during repetitive rehabilitation motions.

An additional extension spring is integrated within the DFAM module, connecting the sliding puller to the module housing. This spring assists in restoring the sliding mechanism and SMA wire to their initial positions after each actuation cycle, preventing tendon slack during cooling and eliminating the need for antagonistic SMA actuators. The use of a passive spring return reduces actuator count, system weight, and material cost while improving repeatability and mechanical reliability [35].

To further enhance recovery efficiency, a PWM-controlled cooling fan is incorporated to accelerate SMA cooling. Unlike fixed speed fans used in earlier systems [29,35], PWM control enables dynamic adjustment of airflow and noise levels based on real time thermal requirements [38]. A compact San Ace 40 1U server fan ($40 \times 40 \times 28$ mm, 12 V, 0.35 A, 16.3 CFM) was selected for its high airflow-to-size ratio and precise speed control capability [53]. PWM-based cooling significantly reduces SMA recovery time, lowers power consumption, and improves user comfort by minimizing acoustic noise, thereby supporting faster and more consistent rehabilitation cycles [29].

Together, the elastic rubber bands, extension spring, and PWM assisted cooling form an efficient passive recovery unit that enables reliable bidirectional finger motion while minimizing system complexity, weight, and energy demand.

(iii) Mounting and Support Unit

In addition to the actuation and passive recovery units, the W-DFAS glove incorporates a dedicated mounting and support unit to ensure precise component alignment, user safety, and ergonomic comfort during operation. The system is built on a wearable glove base [54] that conforms to the hand anatomy and is secured using adjustable Velcro straps [55] and self-adhesive buckle (SAB) straps [56], enabling rapid fitting and stable fixation around the wrist and fingers. These mounting elements are essential for maintaining consistent positioning of the actuation components and preventing glove displacement during repetitive finger motion.

To enhance stability and customization, finger hooks and tendon wire guides located at the proximal and intermediate phalanges are additionally secured using Velcro straps, minimizing slippage during actuation. Non-slip fingerstalls are fixed at the fingertips to act as pivot points during flexion and extension while preventing glove lifting or stretching under load [57]. Experimental observations indicated that omission of these fixation elements leads to noticeable glove displacement and reduced actuation consistency, underscoring their importance in maintaining reliable system performance.

The mounting and support unit also provides dedicated housing for the SMA actuators and DFAM module, ensuring controlled tendon routing and stable mechanical integration. Although these components do not directly generate motion, they play a critical role in preserving efficient force transmission from the SMA actuators to the fingertips, maximizing achievable range of motion, minimizing energy losses, and maintaining overall functional reliability of the system.

To further improve actuation efficiency, custom SMA wire guides were integrated into the design. These guides constrain lateral wire motion, maintain consistent tension, and prevent buckling during

heating and cooling cycles. By preserving a well-defined wire path, the guides ensure that SMA contraction is effectively converted into mechanical displacement. Fabricated from polylactic acid (PLA), the guides offer low friction, low weight, and ease of manufacture, contributing to smoother motion, improved repeatability, and a compact actuator layout.

The finger level components including tendon guides, hooks, PE lines, elastic elements, and fixation straps are illustrated schematically in Fig. 5; while corresponding photographic views of the palm and dorsal sides of the glove are shown in Fig. 6. The fully assembled W-DFAS glove is presented in Fig. 7, highlighting (a) the palmar configuration and (b) the dorsal configuration of the complete system.

All DFAM components were fabricated using PolyLite™ PLA filament and printed by fused deposition modeling (FDM) under manufacturer recommended conditions to ensure dimensional accuracy and mechanical reliability [58–62]. PLA was selected for its low weight, adequate stiffness, and thermal stability, making it suitable for DFAM structural parts operating below its glass transition temperature [63].

4. Results and Discussion

4.1. Fingertip force

The fingertip force performance of the W-DFAS glove was evaluated to assess its ability to provide functional assistive force during hand rehabilitation. Force measurements were conducted under a single representative actuation condition using PWM-controlled current of 2.2 A applied for 1 s, selected as the optimal operating point balancing force output, thermal safety, and recovery time.

To capture posture dependent variations in force generation, measurements were performed across four representative finger postures (P1–P4), ranging from full extension (P1) to full grasp configuration (P4), as illustrated in Table 5. These postures reflect the natural progression of finger flexion during functional hand closing and allow evaluation of force transmission under varying joint angles and tendon routing geometries. Fingertip forces were measured using calibrated load-cell sensors positioned beneath the fingertips. For postures P1–P3, two load cells enabled independent force measurement of paired fingers as shown in Fig. 8 (a), while for posture P4, where full flexion caused finger overlap, a single load-cell configuration was employed to measure the combined fingertip force, as illustrated in Fig. 8 (b).

For each posture, steady-state force values during SMA contraction were extracted, and the average fingertip force was calculated by taking the mean force across the four postures (P1–P4) as illustrated in Fig. 9 (a) and (b). This averaging approach provides a single representative metric that accounts for posture dependent variability and better reflects functional assistive performance during daily hand-use tasks.

The results demonstrate that the DFAM-6X-based W-DFAS glove can generate consistent and repeatable fingertip forces sufficient to overcome passive finger resistance across the full range of motion. These findings validate the effectiveness of the proposed actuation and transmission design for wearable hand rehabilitation applications.

4.2. Current and voltage

Fig. 10 shows the time domain electrical response of the SMA actuation system under PWM-controlled excitation at 2.2 A for 1 s. The measured current exhibits a stable plateau close to the target value, indicating reliable regulation by the PWM driver with minimal transient fluctuation. Correspondingly, the voltage stabilizes near the theoretical value (≈ 10.96 V), while the calculated electrical power reaches approximately 24.1 W, consistent with predictions based on the SMA wire resistance (4.98 Ω). A slight voltage decrease during the heating phase is observed, attributed to temperature dependent resistance variation of the NiTi SMA wire. Upon termination of excitation, the current and voltage rapidly drop to zero, confirming proper MOSFET

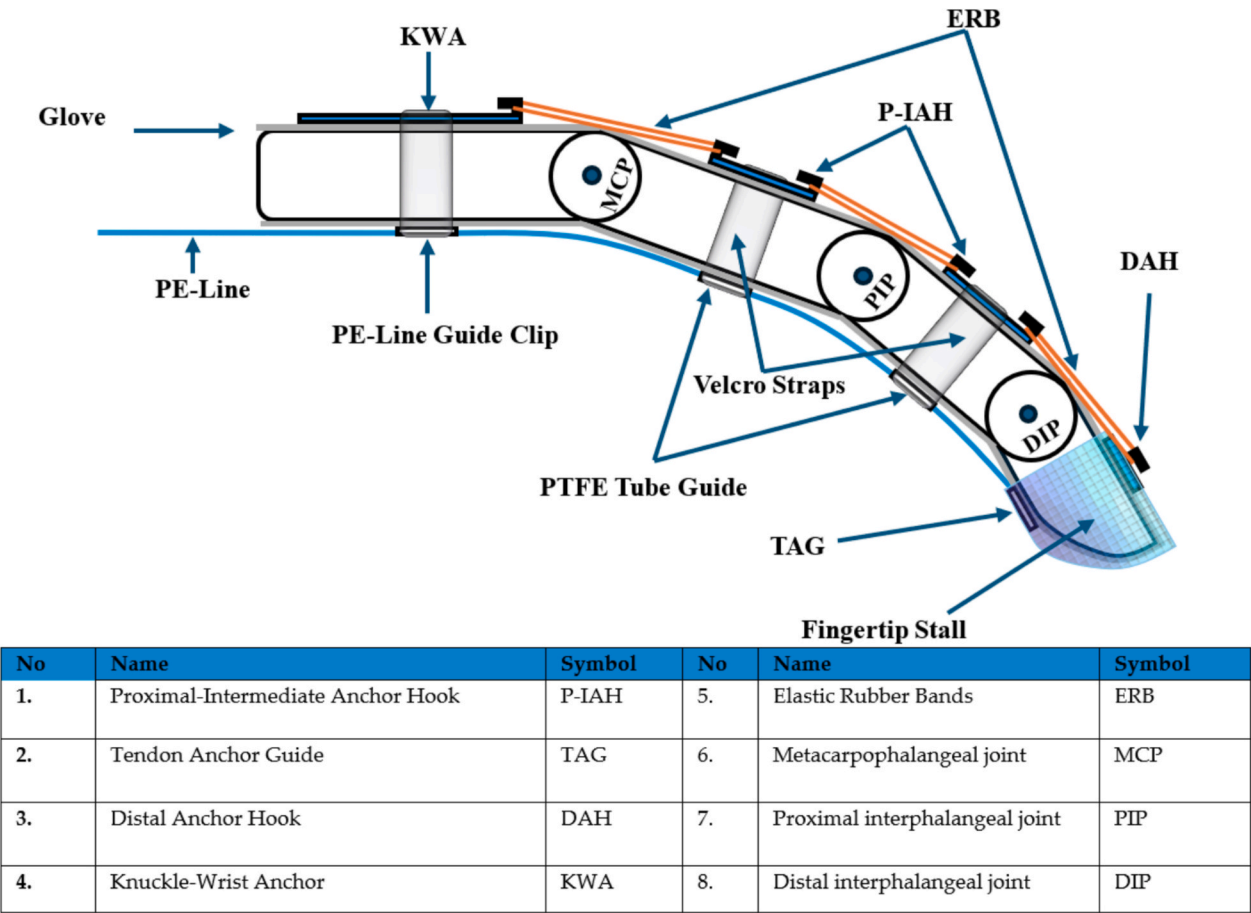


Fig. 5. Schematic of components of the index finger: guides, hooks, PE line, elastic rubber bands, and Velcro straps.

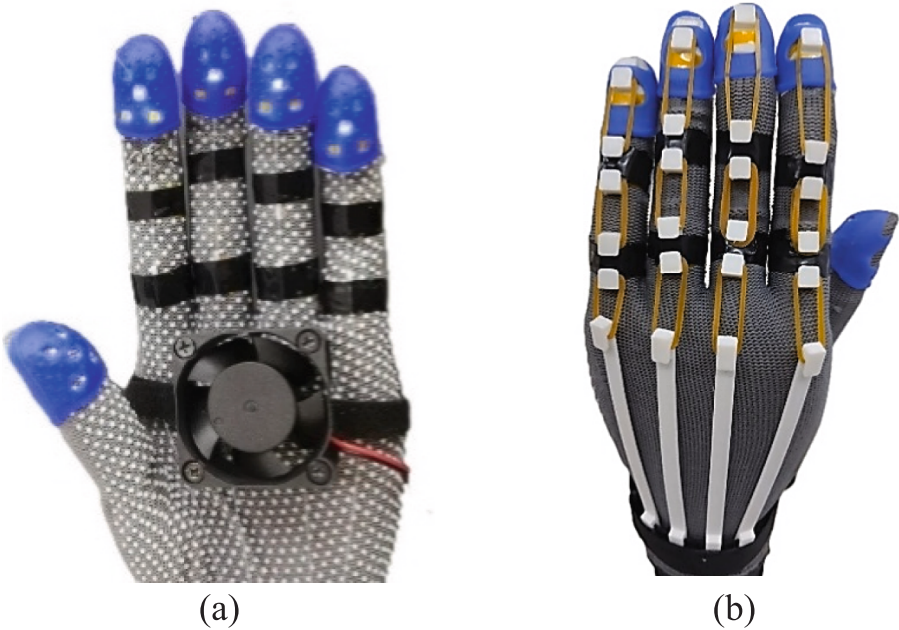


Fig. 6. Finger component guide hooks, PE line, elastic rubber bands, and Velcro straps (a) palm view and (b) dorsal (back) view.

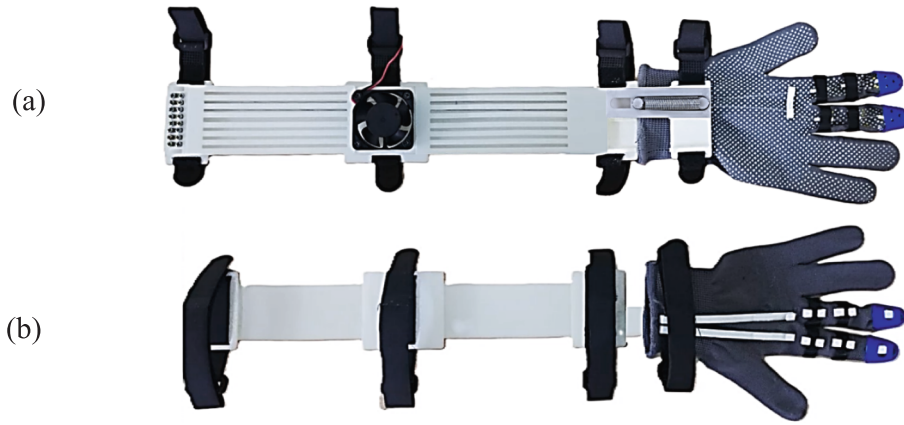


Fig. 7. W-DFAS glove showing:(a) Palm view and (b) Dorsal (back) view.

Table 5
Finger Postures and Corresponding Joint Flexion Angles.

Posture	Description	MCP (°)	PIP (°)	DIP (°)
P1	Fully extended	0	0	0
P2	DIP flexion only	0	0	20
P3	Functional bend	0	30	45
P4	Full grasp posture	80	50	45

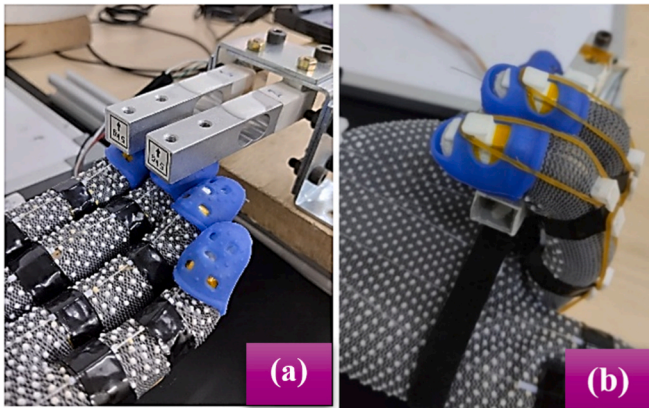


Fig. 8. Fingertip force measurement in (a) Posture P1-P3; (b) Posture P4.

switching and effective safety cut-off. These results demonstrate stable, repeatable, and well-controlled electrical input to the SMA actuator, supporting reliable thermal activation and consistent mechanical performance during rehabilitation operation.

4.3. Finger flexion

Table 6 presents the finger flexion performance of the W-DFAS glove under five PWM duty cycles (60–100%) with the SMA actuators driven at 2.2 A for 1 s. Increasing the PWM duty cycle resulted in progressively larger finger flexion, where lower levels (60–70%) produced partial bending, while higher levels (90–100%) achieved near full flexion resembling a functional grasp. The results demonstrate stable and repeatable actuation, confirming that PWM control effectively regulates SMA contraction intensity and enables adjustable finger bending suitable for different rehabilitation requirements.

4.4. Finger joint angle analysis during heating

Finger joint kinematics of the SMA-based rehabilitation glove were

evaluated during the heating phase using high resolution video recordings. Still frames extracted at selected time points were analyzed in ImageJ to estimate the metacarpophalangeal (MCP), proximal interphalangeal (PIP), and distal interphalangeal (DIP) joint angles. Joint angles were calculated by identifying anatomical landmarks and measuring inter-segment angles using the ImageJ Angle Tool after spatial calibration [64,65]. Fig. 11 shows that at 100% PWM, the glove achieves its maximum finger flexion, with pronounced MCP, PIP, and DIP rotation and clear fingertip displacement toward the palm. The nearly identical bending patterns across all fingers confirm uniform SMA force transmission through the dual finger actuation mechanism, enabling a coordinated and functional grasp.

Fig. 12, shows the total bending angle ($\theta_{\text{Total}} = \theta_{\text{MCP}} + \theta_{\text{PIP}} + \theta_{\text{DIP}}$) of the four fingers under PWM-controlled actuation at 2.2 A for 1 s. Under this condition, the index and middle fingers achieved total flexion angles exceeding 200°, while the ring and little fingers reached values above 190°, indicating strong SMA contraction and effective multi-joint engagement. The similarity in total bending between the index–middle pair and the ring–little pair confirms uniform force transmission through the DFAM mechanism. These results demonstrate that the 2.2 A–1 s excitation provides rapid and sufficient flexion to reach a functional grasp posture, making it well suited for high intensity or fast response rehabilitation tasks.

Fig. 13 shows that the PWM duty cycle directly influences the flexion posture of the index finger. At 2.2 A, higher PWM levels (90–100%) produce near maximal MCP, PIP, and DIP flexion, while reducing the duty cycle to 60–70% results in a clear decrease in bending, particularly at the DIP joint. This behavior indicates that effective SMA activation requires sufficient average thermal input, with a sharp reduction in flexion occurring at lower PWM levels.

4.5. Finger posture recovery during cooling

A sequential time-lapse of the index–middle finger pair was extracted from the recorded experimental video to evaluate finger posture recovery following SMA actuation (Fig. 14). Only the index–middle pair is presented here, as this configuration represents the core dual finger actuation mechanism adopted in the W-DFAS system.

After each flexion event, the actuated SMA wires entered a cooling phase during which finger extension was gradually restored. Without forced cooling, the SMA wires required more than 15 s to return the fingers to their neutral position due to limited natural heat dissipation. When forced convection was introduced via the PWM-controlled fan, the recovery time was significantly reduced to approximately 7 s, demonstrating clear thermal management benefit for cyclic rehabilitation tasks.

The flexion phase required 1 s, depending on the applied duty cycle

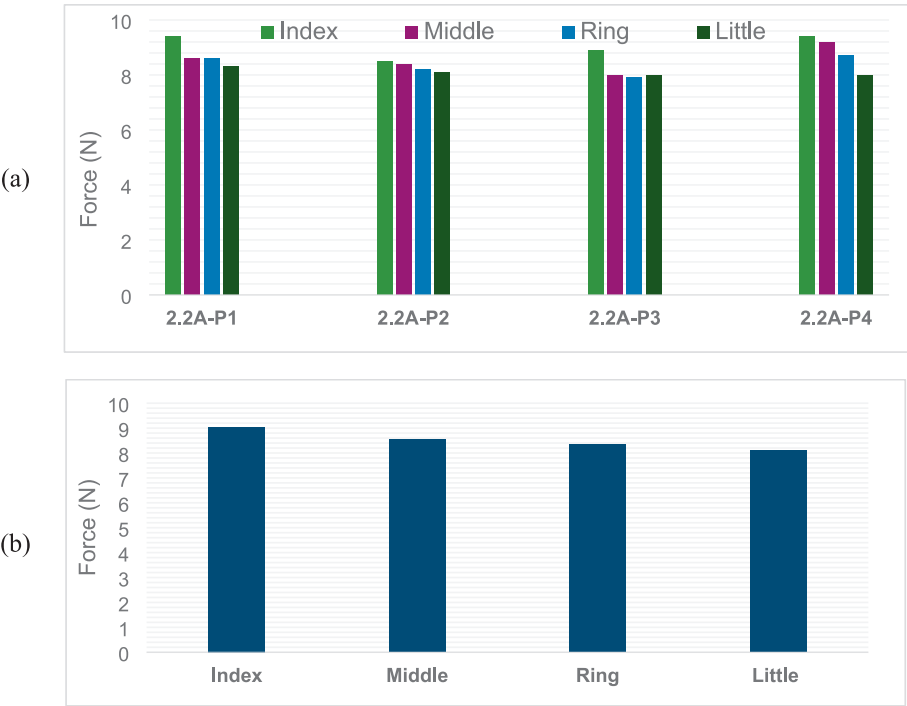


Fig. 9. Force of the sma glove: (a) force distribution across p1–p4 and currents, (b) average fingertip force per finger for 2.2a-1sec.

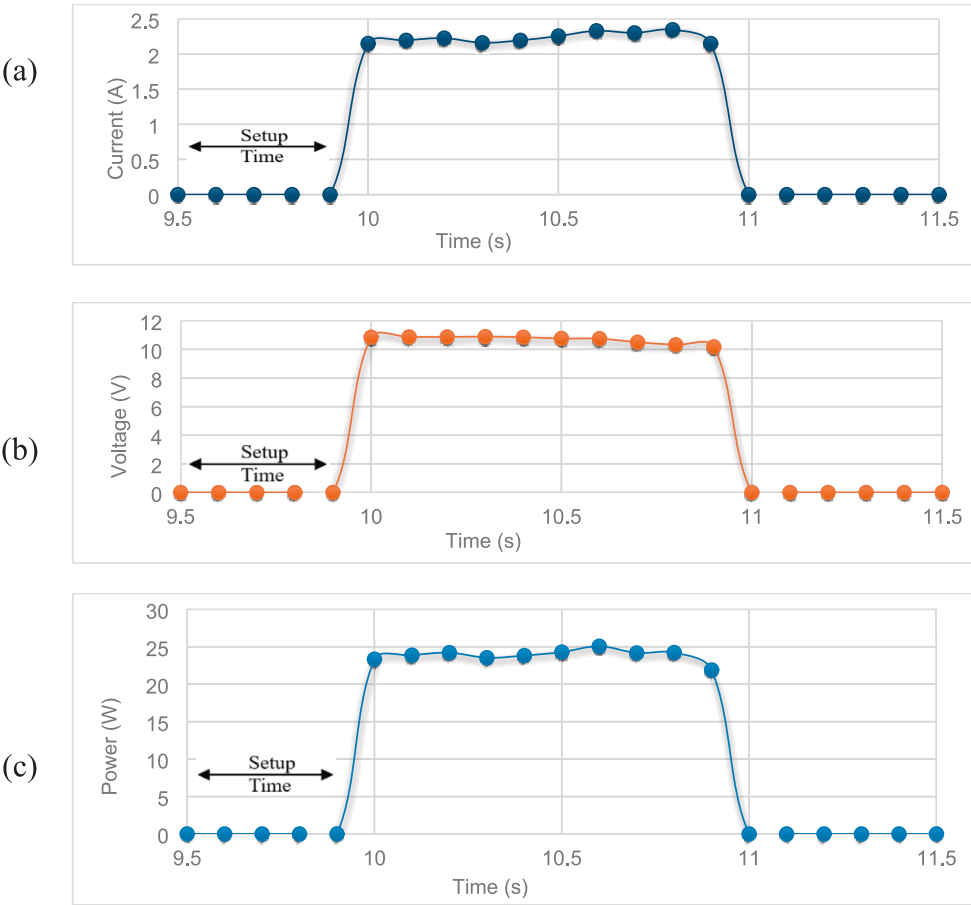
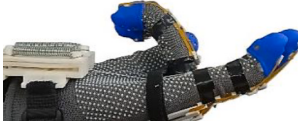


Fig. 10. Real Time Electrical Response of the W-DFAS at 2.2A –1 sec; (a) Current, (b) Voltage, and (c) Power Profiles.

Table 6
Finger Flexion Response at Different PWM Duty Cycles (2.2 A for 1 s Actuation).

PWM%	Index-Middle	Ring-Little	Four Fingers
60			
70			
80			
90			
100			

and current amplitude. Consequently, one full flexion–extension rehabilitation cycle required approximately 8 s, corresponding to a practical rate of 7 full cycles per minute. The system also achieved a practical and repeatable operation rate of approximately seven cycles per minute under the tested conditions, which is notable for a compact SMA-based wearable system; however, detailed analysis of long-term cyclic behavior and SMA hysteresis effects were beyond the scope of this study. This cycle frequency falls within acceptable ranges for hand rehabilitation protocols where moderate speed repetitive activation is typically employed to support neuromuscular stimulation and joint mobility training.

4.6. Grasping performance evaluation

During the grasping experiments, the glove was positioned horizontally with the hand initially in an open configuration. The test object was placed on the palm, after which the SMA actuators were activated, causing the fingers to flex and wrap around the object. Although the object was initially pre-positioned, the grasp was achieved through active tendon driven finger closure, generating sufficient contact forces to enclose and retain the object. This approach was adopted to ensure consistent initial conditions and repeatability across all trials.

The grasping evaluation assessed the ability of the W-DFAS glove to manipulate everyday objects relevant to Activities of Daily Living (ADL) and rehabilitation training, as illustrated in Fig. 15, using four clinically

meaningful grasp categories: cylindrical, spherical, box-shaped, and irregular (Santello et al., 2016; Feix et al., 2015). The glove successfully enclosed cylindrical objects such as bottles, tape rolls, spray containers, and pipes ($\approx 20\text{--}52$ mm diameter), achieving full finger wrapping and stable contact. Spherical objects, including fruits and stress balls ($\approx 53\text{--}65$ mm diameter), were grasped securely with smooth curvature conformity, supporting coordinated finger flexion. Rectangular and flat objects such as gum packs, juice boxes, tissue packs, and remote controls were handled reliably, demonstrating adaptability to prismatic surfaces commonly encountered in daily environments. Additionally, irregularly shaped items such as tools and spools were grasped without observable slippage, confirming adaptability to complex real world objects. Across all categories, the glove maintained stable posture and consistent contact while handling objects weighing approximately 20–400 g, highlighting its suitability for functional, task oriented hand rehabilitation and ADL focused therapy.

4.7. DFAM transmission analysis

The DFAM transmission characteristics—amplification gain, stroke reduction, efficiency, and frictional losses—were constant for all actuation conditions because the DFAM geometry and slider mechanism remained unchanged. Based on the calibration posture (MCP 95.407°, PIP 50.993°, DIP 67.447°), the DFAM demonstrated a fixed experimental amplification gain of 3.19X, corresponding to a 68.7% reduction

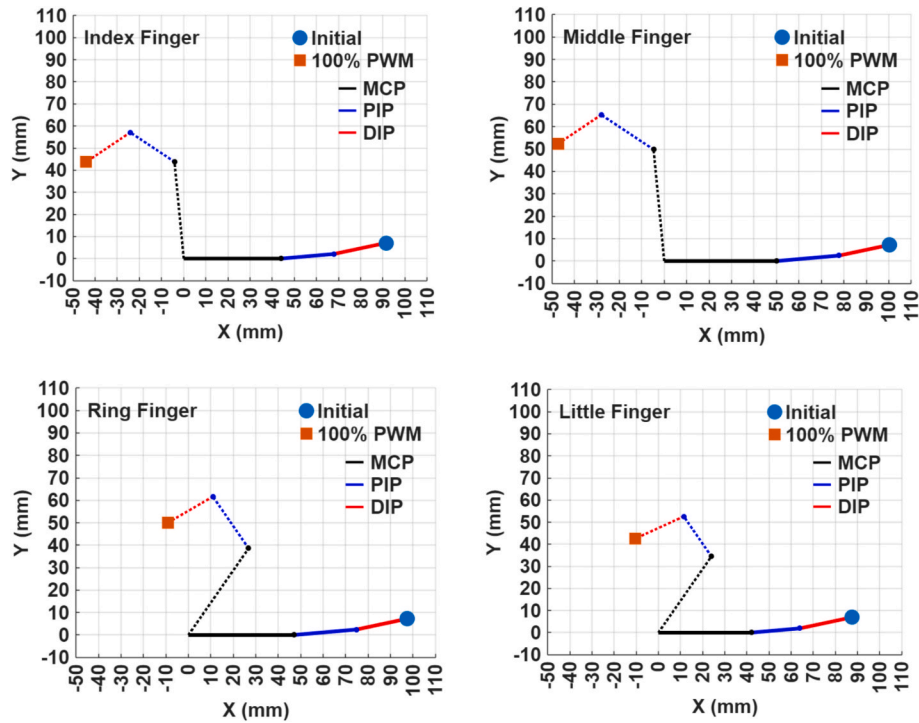


Fig. 11. Index, middle, ring, and little finger postures under 2.2A-1 sec with PWM control (100% duty cycles).

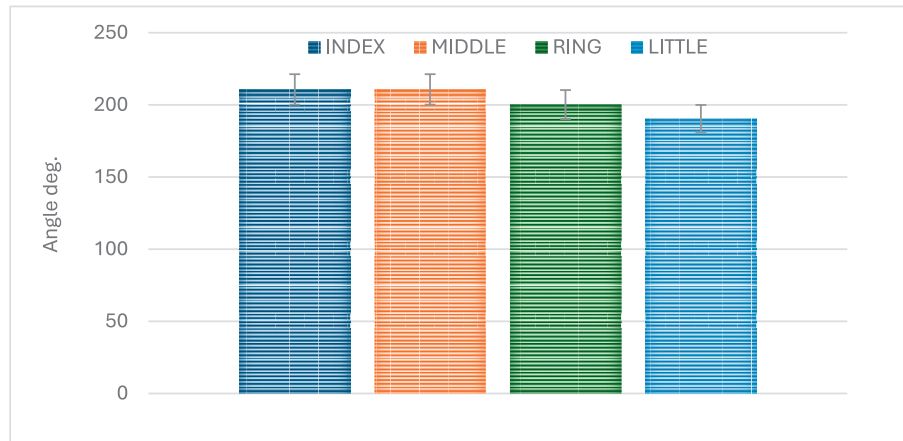


Fig. 12. Total MCP-PIP-DIP bending angles of the index, middle, ring, and little fingers at 2.2 A for 1 s.

in required actuator stroke. Although the theoretical amplification ratio of the DFAM mechanism is 6X based on ideal pulley kinematics, the experimentally measured gain was lower because of non-ideal transmission losses within the prototype. The main loss sources include friction between the PE line and the 3D-printed guide features, friction at the PE line-PTFE rod interfaces and sliding friction between the puller and the DFAM base during actuation. Tendon bending along curved routing paths and slight geometric misalignment during fabrication and assembly also contribute to additional losses. These effects collectively reduce transmission efficiency and lead to a lower effective amplification than that predicted under ideal conditions.

Table 7, presents the joint angle measurements extracted from ImageJ and the corresponding DFAM kinematic calculations performed using MATLAB for the PWM-2.2A-1 s condition. As PWM duty cycle decreases from 100% to 60%, the MCP-PIP-DIP angles and total joint flexion decrease accordingly, indicating reduced tendon travel requirements. Without DFAM, the tendon displacement required at full

PWM reaches 38.33 mm, decreasing to 21.62 mm at 60% PWM. When the DFAM mechanism is applied, the required actuator stroke is substantially reduced. At 100% PWM, the DFAM produces the same finger posture with only 12.00 mm of SMA stroke, compared to 38.33 mm without amplification. This reduction remains consistent across all PWM levels. Because SMA strain is limited to approximately 4%, the corresponding SMA wire length required without DFAM ranges from 540–958 mm, whereas the DFAM reduces this requirement to 169–300 mm, keeping the actuator compact and feasible for wearable systems.

These results confirm that DFAM provides a significant kinematic advantage by converting small SMA strokes into large tendon displacements, enabling full range finger flexion using much shorter and faster SMA actuators.

Fig. 16 shows the effect of PWM duty cycle on the SMA wire length required to achieve the target MCP-PIP-DIP flexion. Without DFAM, the limited $\approx 4\%$ contraction of NiTi requires very long SMA wires, with lengths of approximately 958 mm at 100% PWM and 540 mm at 60%

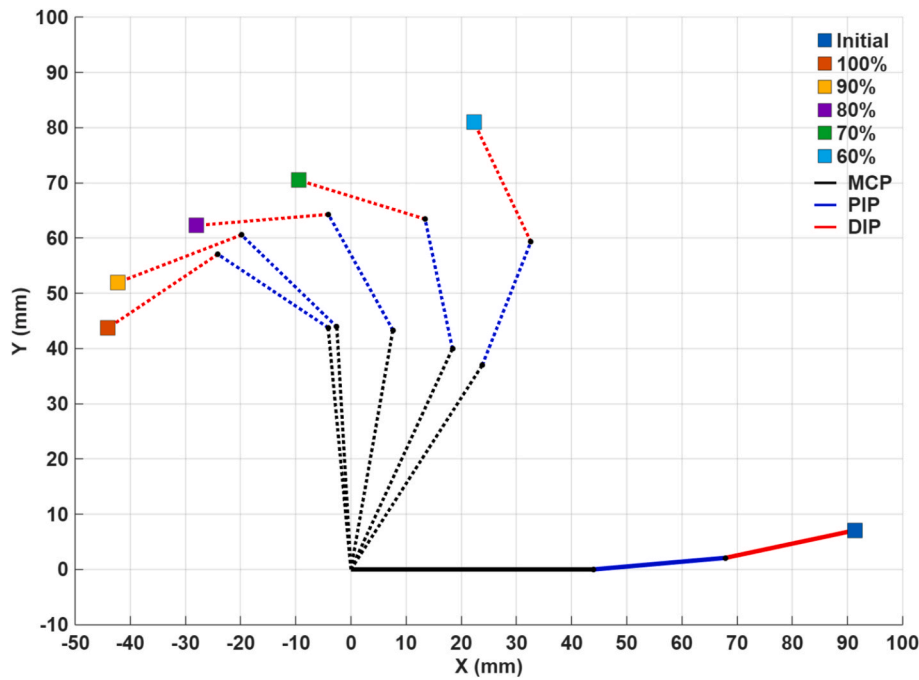


Fig. 13. Index finger postures under different PWM duty cycles at 2.2 A -1 s.

PWM, which are impractical for wearable systems. With the DFAM-6X applied, the required SMA length is reduced to 300 mm at 100% PWM and 169 mm at 60% PWM, corresponding to a consistent 3.19x reduction that matches the experimental amplification gain. The clear separation between the curves confirms the DFAM's effectiveness in converting short SMA strokes into large tendon displacements, enabling compact, faster, and more energy efficient wearable actuation.

4.8. Comparative evaluation with existing soft robotic

To contextualize the performance of the developed W-DFAS glove within the broader field of wearable assistive technologies, its experimentally validated results were compared with previously reported soft robotic and SMA-based glove systems published between 2015 and 2024. The W-DFAS achieved a fingertip force of (8–9) N, which falls within the functional range required for Activities of Daily Living (ADL), typically 7–10 N. This value is comparable to several established SMA-based systems such as the 2016 SMA assistive glove (≈ 12 N) [34], the 2017 ASR glove (≈ 10 N) [29], and the 2021 HMD glove (≈ 8 N) [31]. Although certain systems report substantially higher output forces—for example, the Soft Packaged SMA Glove (14.3 N) [42] or the system of multi-spring SMA array for elbow (not finger) exceeding > 48 N [43] these devices often rely on heavier actuation modules, complex routing, or forearm mounted mechanical assemblies. In contrast, the W-DFAS offers a practical balance between force generation, system weight, and mechanical simplicity, making it more suitable for wearable rehabilitation.

From a design perspective, the proposed W-DFAS differs from many existing SMA-based gloves and smart grippers by integrating a dual finger differential actuation architecture with a DFAM-based displacement amplification mechanism. Unlike conventional one-actuator-per-finger systems, this configuration allows a single SMA actuator to drive two fingers simultaneously, reducing system complexity while maintaining coordinated motion. In addition, the use of a double U-shaped SMA configuration enhances force generation within a compact layout, while the hybrid recovery strategy eliminates the need for antagonistic SMA actuation, thereby reducing power consumption and overall system weight.

In terms of joint kinematics, the W-DFAS demonstrated a total

bending range of 213° (DIP 67° , PIP 51° , MCP 95°), exceeding several classical SMA systems such as the 2016 SMA glove (160°) [34] and the 2020 SMA single finger exoskeleton (109°) [37]. While a few highly deformable prototypes such as coiled-SMA soft hands achieving extreme bending angles up to 240° [41] surpass this range, their corresponding force outputs are very low (< 1 – 2 N), limiting their suitability for functional grasping. The W-DFAS therefore offers an advantageous combination of realistic joint angles and functional output force, directly supporting rehabilitation and assistive activities.

The total system weight of the W-DFAS (≈ 370 g without battery; ≈ 120 g for glove + DFAM module) positions it among the lightest SMA-based rehabilitation gloves. It is substantially lighter than the glove (602 g) in 2018 [35], the Adaptive Motorized Exo-Glove (562 g) [66], and the MataPro-1 system (~ 1.2 kg) [38]. Although some elastomer-based or textile actuators weigh less (< 150 g) [67], they generally provide limited force and slower response. By contrast, the W-DFAS combines low weight with adequate force and fast cycle performance, making it more balanced for practical use.

A key mechanical advantage of the W-DFAS is its passive extension mechanism, realized through an Elastic Rubber Band (ERB) and an extension spring, eliminating the need for a dedicated extensor actuator. Many prior systems rely on active antagonistic actuation, such as dual SMA wires, linear motors, or pneumatic extension layers [31,39], which increases energy consumption, actuator fatigue, system cost, and mechanical complexity. The passive extension strategy of the W-DFAS significantly reduces electrical power requirements, improves durability, minimizes heat cycling on SMA wires, and decreases overall system weight. This design decision contributes to both the glove's mechanical efficiency and its suitability for long duration rehabilitation sessions.

The incorporation of a PWM-controlled cooling fan enabled the W-DFAS to achieve 6–8 cycles per minute, fulfilling and exceeding the ADL requirement of approximately 5 cycles/min. This cycle rate outperforms systems relying solely on natural cooling—such as the 2016 SMA glove [34], the 2020 SMA single finger design [38], and the 2021 HMD glove [31]—while providing comparable performance to high-power fan cooled systems (e.g., 2023 Soft Packaged SMA Glove, ~ 10 cycles/min [42]) but with significantly lower energy consumption and simpler hardware.

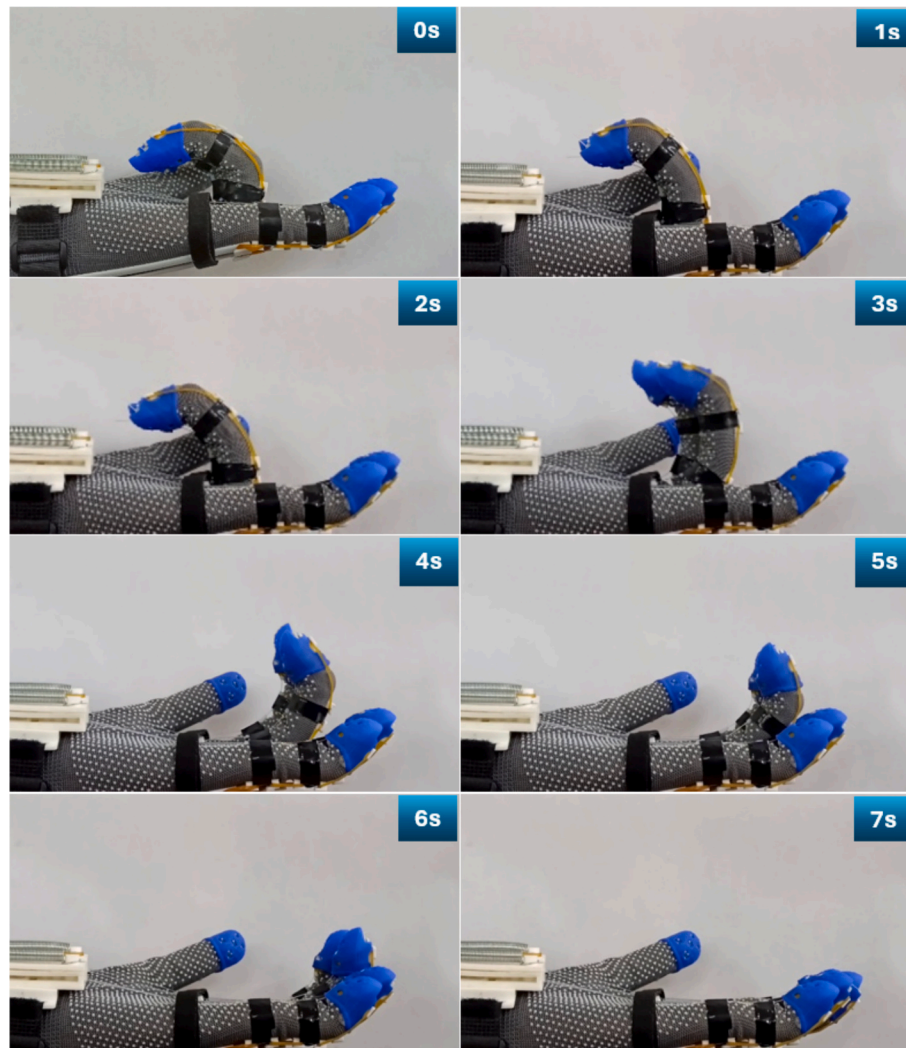


Fig. 14. Index–middle finger recovery during forced convection SMA cooling (0–7 s).

Overall, the comparative evaluation demonstrates that the W-DFAS glove offers a well-optimized combination of fingertip force (8–9 N), bending capability (213°), lightweight structure, passive extension mechanism, and functional cycle rate ($\sim 8/\text{min}$). These attributes collectively position the W-DFAS as a practical, energy efficient, and high performance SMA-based rehabilitation glove. This combination of displacement amplification, dual finger actuation, reduced actuation complexity, and efficient passive recovery represents a capability that is difficult to achieve simultaneously in many existing SMA-based wearable glove systems. A detailed summary of this property is presented in Table 8.

5. Conclusion

The proposed W-DFAS demonstrates that differential dual finger actuation can be practically realized in an SMA-driven wearable glove by combining DFAM_6X amplification with a compact transmission layout and hybrid recovery. At 2.2 A for 1 s and 100% PWM, the glove achieved coordinated four finger flexion with total bending angles exceeding 200° for the index and middle fingers and 190° for the ring and little fingers, enabling rapid formation of a functional grasp posture. The DFAM provided a fixed experimental gain of 3.19X, reducing actuator stroke requirements by 68.7% and decreasing SMA wire length from approximately 958 mm to 300 mm, thereby improving wearability and system feasibility. PWM-controlled fan cooling reduced recovery

time to approximately 7 s and enabled about 7 actuation cycles per minute, supporting repetitive rehabilitation exercises. Finally, successful grasping across four object categories ($\approx 20\text{--}400\text{ g}$) highlights the system's potential for ADL focused, task oriented hand rehabilitation. The proposed W-DFAS introduces a dual finger differential actuation mechanism combined with DFAM-based amplification and passive recovery, enabling reduced complexity, improved energy efficiency, and practical cyclic performance compared to existing SMA-based gloves. Despite the promising performance of the proposed W-DFAS system, several limitations remain that will be addressed in future work. First, comprehensive human subject trials will be conducted to evaluate safety, comfort, and functional rehabilitation effectiveness under real usage conditions. Second, long term cyclic durability testing will be performed to assess the fatigue behavior of SMA wires and the reliability of the mechanical transmission system under repeated actuation. Future work will also include detailed characterization of SMA hysteresis and long term cyclic behavior to evaluate actuation stability, repeatability, and fatigue performance under repeated rehabilitation cycles. In addition, future work will include quantitative characterization and optimization of the stiffness of passive recovery elements to further improve extension dynamics, system efficiency, and control performance. Furthermore, efforts will focus on improving the transmission efficiency of the DFAM mechanism by reducing frictional losses and enhancing displacement gain. This includes optimization of tendon

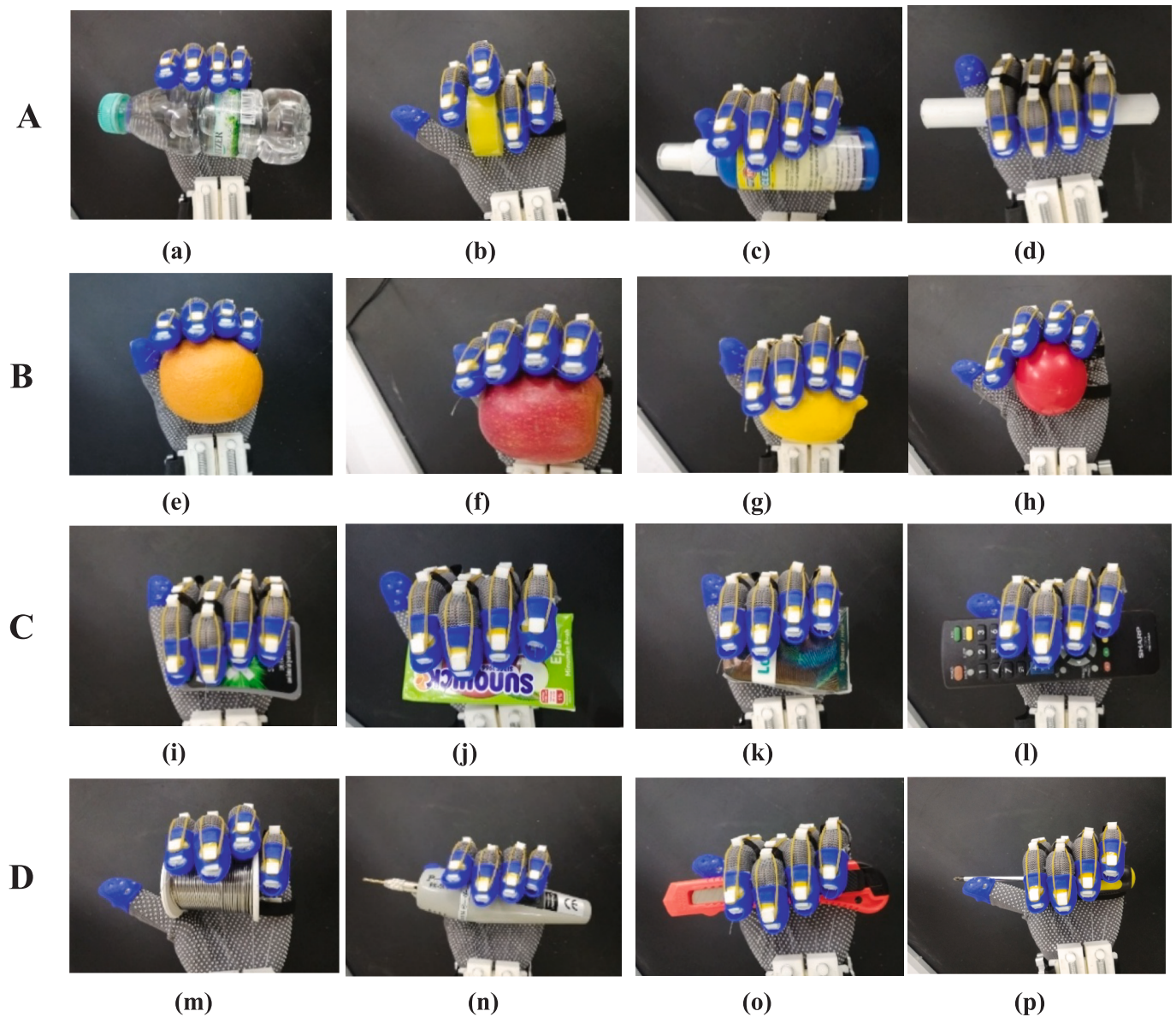


Fig. 15. Grasping tests across four object categories: (A) Cylindrical objects (a–d), (B) Spherical objects (e–h), (C) Box-shaped objects (i–l), and (D) Irregular objects (m–p).

Table 7
DFAM-6X Kinematic Transmission Results for Index Finger at PWM-2.2A-1 s.

Parameter	100%	90%	80%	70%	60%
MCP angle (°)	95.407	93.344	80.052	65.285	57.246
PIP angle (°)	50.993	42.695	39.090	36.647	11.225
DIP angle (°)	67.447	65.009	65.659	60.995	46.971
Total joint flexion (°)	213.847	201.048	184.801	162.927	115.442
Tendon displacement (no DFAM) (mm)	38.33	36.21	33.64	30.01	21.62
Required SMA stroke with DFAM (mm)	12.00	11.34	10.53	9.40	6.77
Required SMA stroke with ideal 6X DFAM (mm)	6.39	6.04	5.61	5.00	3.60
Required SMA length (no DFAM) (mm)	958.1	905.4	841.0	750.3	540.5
Required SMA length with DFAM (mm)	300.0	283.5	263.3	234.9	169.2

routing to minimize curvature induced losses, replacement of sliding contacts with rolling or bearing supported elements, and refinement of surface finishing and material pairing at contact interfaces (e.g., polymer-PTFE interactions).

Finally, improved fabrication tolerances and alignment strategies will be explored to reduce assembly induced inefficiencies and enhance overall mechanical performance. Although the current system operates under open-loop PWM control, future work will focus on the development of closed-loop control strategies by integrating feedback sensors such as flex sensors, force sensors, or temperature sensors on the SMA wires. These sensors will enable real time monitoring of finger motion and actuator state, allowing adaptive adjustment of the PWM input to improve motion accuracy, safety, and personalized assistance for stroke and hand injury rehabilitation applications.

CRediT authorship contribution statement

Q.Y. Hamid: Writing – original draft, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **W.Z. Wan**

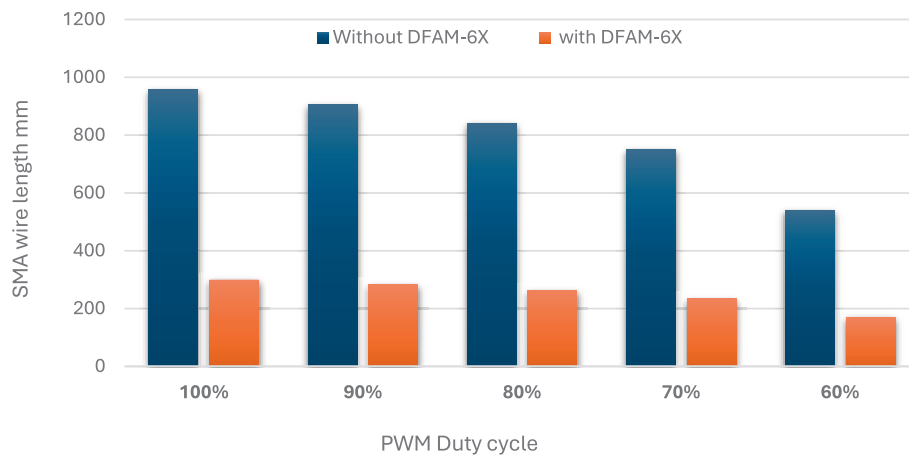


Fig. 16. SMA Wire Length with and without DFAM-6X Across PWM Duty Cycles.

Table 8

Specifications of the W-DFAS Glove.

Parameter	Specification (W-DFAS, 2025)
SMA length / actuator type	600 mm total (folded 300 mm effective)
Index lengths (MCP–PIP–DIP)	44 mm – 24 mm – 24 mm
Index thickness of knuckles (MCP–PIP–DIP)	24 mm – 22 mm – 20 mm
Weight	≈120 g (glove + DFAM + tubes) ≈250 g actuator module (PWM driver + MOSFET + fan) ≈370 g total without battery
SMA diameter / type	0.38 mm Flexinol LT SMA wire
Index Fingertip force	~ 9N
Index: Max bending angles (θ_1 , θ_2 , θ_3)	DIP: 67°, PIP: 51°, MCP: 95°, Total = 213
Cooling system	PWM-controlled cooling fan
Actuating mechanism	Dual Finger Amplification Mechanism (DFAM) for two-finger simultaneous actuation
Extension mechanism	Passive ERB + extension spring (no extensor actuator required)
Control	Arduino Uno, open-loop PWM SMA actuation
Flexion–extension rate	Heating: 1 s
Cooling time	~ 15 s natural air convection ~7 s using PWM cooling fan
Open-close (cycles)	≈ 8 cycles/min

Hasan: Writing – review & editing, Supervision, Project administration, Funding acquisition. **M.A. Azmah Hanim:** . **A.A. Nuraini:** . **M.N. Hamidon:** Writing – review & editing, Supervision, Funding acquisition.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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