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Twisted String Actuators in Wearable Robotics: Review and Perspective Across Rehabilitation, Assistance, Augmentation, and Haptics

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(Review Paper)

***Abstract*—Twisted String Actuators (TSAs) have emerged as a compelling soft actuation paradigm for wearable robotic systems, offering high force output within a compact, lightweight, and mechanically compliant form factor. This systematic review provides a comprehensive analysis of TSA-based wearable devices reported in the literature between 2013 and 2026, synthesizing 34 functional prototypes identified through a structured search of Scopus and Google Scholar databases. Devices are categorized according to two orthogonal frameworks: anatomical target segment and primary application domain. The review examines the biomimetic foundations of TSA operation, its analogy to the human musculoskeletal system, and the key mechanical design decisions governing actuator configuration, force transmission strategy, degrees of freedom, structural substrate, and sensing modality. A progressive shift from rigid toward soft and hybrid architectures is identified across the review period, consistent with user acceptance requirements in clinical and industrial settings. Intent-driven control strategies fusing surface electromyography and inertial measurement units have emerged as the dominant paradigm for assistive and augmentation devices. Persistent open challenges include the non-linear kinematics of TSA force-displacement relationships, the near-total absence of long-term mechanical durability data, and the lack of real-world clinical validation. Notable anatomical gaps, particularly at the shoulder and cervical complex, are identified as high-priority directions for future development. Collectively, the findings position TSA-based wearables as a rapidly maturing technology with strong potential for translation into mainstream rehabilitation and human augmentation platforms.**

***Index Terms*—Twisted String Actuator, wearable device, exoskeleton, haptic.**

I. Introduction

THE rapid proliferation of wearable technology has fundamentally altered the landscape of human-machine interaction, transitioning from simple monitoring devices to active, force-multiplying systems. In contemporary research, wearable devices have become ubiquitous, serving as essential tools in fields ranging from clinical rehabilitation to industrial ergonomics. However, actuation remains one of the most consequential design decisions at this layer of the system: pneumatic, hydraulic, electric, shape memory alloy (SMA), variable stiffness actuator (VSA), and tendon-driven, each present a distinct profile of power density, control precision, weight, backdrivability, and compliance, and no single paradigm is uniformly superior across these criteria. Among the compliant, remotely-actuated options, the Twisted String Actuators (TSA), though currently less common in wearable devices than conventional rotary motors or Bowden-cable tendon drives, have emerged as a highly effective solution. The growing interest in TSA-based wearable devices is driven by their unique ability to provide significant linear force within a compact, lightweight, and flexible form factor, making them ideal for integration into the soft fabric of wearable garments.

A defining characteristic of the TSA mechanism is its mechanical adaptability, which allows it to be tailored to the specific biomechanical demands of different regions of the human body. Unlike bulky traditional motors that are difficult to mount on the extremities, the slender profile of TSAs enables their application across diverse anatomical segments. In the upper limbs, TSAs are frequently utilized in robotic gloves and exoskeleton to facilitate grasping and reaching movements. For the lower limbs, they provide the high-torque assistance required for gait stabilization and knee support during locomotion. Furthermore, recent innovations have seen the integration of TSAs into trunk-based systems, such as lumbar exoskeletons designed to reduce spinal compression during heavy lifting. This versatility is a key focus of our study, as we analyze how the TSA's scalability allows it to serve as a modular solution for the entire human kinetic chain.

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While several existing reviews in the literature have addressed the broader field of soft robotics and wearable exosuits [1], [2], [3], a dedicated synthesis focusing exclusively on the diverse implementations of TSA mechanisms is still missing. Previous surveys often categorize actuators by their material composition or general power source, frequently overlooking the nuanced mechanical advantages and specific control challenges inherent to string-based twisting and coiling. This systematic review fills that gap by providing a comprehensive analysis of the current state of the art, focusing specifically on devices that exploit the TSA mechanism. We categorize these technologies according to their target anatomical regions and functional objectives, spanning four primary pillars: augmentation for performance enhancement in healthy users, assistive technology for the elderly and mobility-impaired, clinical rehabilitation for recovery, and haptic feedback for immersive teleoperation and virtual reality. By synthesizing recent advancements this paper provides a roadmap for the future of compliant, high-performance wearable systems.

A. Actuation Technologies for Wearable Robots: A Comparative Rationale

Before motivating the focus of this review on TSA-based devices specifically, it is necessary to situate the TSA within the broader landscape of actuation technologies available for wearable robotics, since the choice of actuator is rarely dictated by a single dominant advantage but rather by a trade-off among several jointly decisive criteria: power density, control precision, weight (assessed both at the joint and system-wide), portability, backdrivability, compliance, dominant material class, and the wearable domains, exoskeletons and haptics, in which each technology is predominantly reported.

Power density and control precision jointly capture raw actuation performance, force or torque per unit mass, and how accurately that output can be commanded in closed loop. Weight and portability separate joint-side mass from the burden of auxiliary hardware (compressors, batteries, control units) needed for untethered use. Backdrivability and compliance both describe safety-relevant softness, but are distinct: backdrivability is the ease of external, unpowered motion, while compliance is intrinsic passive elasticity under load. Material and wearable application, finally, indicate practical constraints on cost and manufacturability, and the domains where each technology is predominantly deployed.

A comparable actuator classification was previously conducted by the authors in the context of elbow exoskeleton design [1], and is extended here to the broader set of criteria and wearable domains relevant to TSA-based devices specifically. Pneumatic actuators offer low joint-side weight and high compliance from air's compressibility, but poor system-level portability due to external compressors, and only moderate control precision. Hydraulic actuators achieve the highest power density and precision through an incompressible fluid, at the cost of the highest weight and lowest backdrivability and compliance, confining them to stationary use. Geared electric motors deliver high power density and precision via high-ratio gearboxes, but the same gearing reduces backdrivability, typically requiring added series elastic actuation to restore compliance. SMA actuators reach the lowest weight and high material-intrinsic compliance through thermally driven phase change, but their slow thermal cycling limits power density and precision. VSAs pair a conventional drive with a dedicated stiffness mechanism, achieving high, tunable compliance and precision comparable to electric motors, at the cost of added weight and complexity. Bowden-cable and TSA actuators, treated together as tendon actuators, both displace the motor from the joint and pull only, but differ in transmission: Bowden cables use a fixed-radius spool for a linear, precisely mapped ratio, while the TSA's ratio is a nonlinear function of twist angle, trading precision and stroke for a lighter, gearless mechanism and higher compliance.

Table I summarizes this comparison across all eight technologies and criteria. It shows that TSAs and Bowden-cable actuators occupy adjacent positions in the design space, both prioritizing low joint-side weight and remote actuation, but trading a predictable, linear transmission for a lighter, gearless mechanism with higher intrinsic compliance. This clarifies that the rationale for the sustained research interest in TSA-based wearable devices surveyed in this review rests on this specific trade-off, compactness and compliance at the expense of stroke and control linearity, rather than on a blanket superiority over pneumatic, hydraulic, or electric actuation, each of which remains the preferred choice in application contexts where its own advantages, respectively compliance under high system weight tolerance, maximal power density, or control bandwidth, dominate the design requirements.

B. Materials and Methods

A systematic literature search was conducted to provide a comprehensive overview of the current state of TSA technology in wearable applications. The primary database used for this review was Scopus, selected for its robust indexing of peer-reviewed literature across engineering and applied sciences. The search query was defined using Boolean operators as follows: TITLE-ABS-KEY (twisted AND string AND actuator OR actuators OR TSAs OR TSA) AND TITLE-ABS-KEY (wearable OR exoskeleton OR haptics). Only publications written in English and published between 2013 and 2026 were considered.

This initial search yielded a total of 70 publications. A screening process was then applied to identify studies relevant to the scope of this review. The primary inclusion criterion was the presence of a functional wearable TSA prototype. Based on this criterion, 27 papers were selected from the Scopus results. The remaining were excluded from the main analysis as they focused on preliminary investigations without prototypes, purely theoretical or mathematical modeling, review articles, or extended analyses of previously published systems. However, selected continuation studies of prior prototypes were retained as supporting references where relevant.

To ensure broader coverage, an additional search was conducted using Google Scholar. This supplementary search identified 7 additional relevant studies that were not indexed or retrieved through the Scopus query.

TABLE I
COMPARISON OF ACTUATION TECHNOLOGIES FOR WEARABLE ROBOTS

Actuator	Power density	Control precision	Weight	Portability	Backdrivability	Compliance	Material	Wearable application
Pneumatic	Medium	Moderate	Low (joint) / high (system)	Low (needs compressor)	Medium	High (air)	Elastomer, fabric	Exoskeleton (assistive)
Hydraulic	High	High	High	Low (bulky pump/reservoir)	Low	Low	Metal, fluid	Stationary / heavy duty
Electric (geared)	High	High	Medium–high	Medium–high	Low–medium	Low (needs SEA)	Metal, rare-earth	Exoskeleton (rehab.)
SMA	Low	Low–moderate	Very low	High	Medium	High (material)	NiTi alloy	Exoskeleton (light duty)
VSA	Medium–high	High	Medium	Medium	Medium–high	High (tunable)	Metal, springs	Exoskeleton (rehab.)
Tendon Actuator								
Bowden cable	Medium	Moderate–high	Low (joint)	High	Medium (sheath friction)	Medium	Steel, polymer cable	Exoskeleton, haptics
TSA	Low–medium	Moderate	Very low	High	High	High (soft, compliant)	Nylon strings	Exoskeleton, haptics

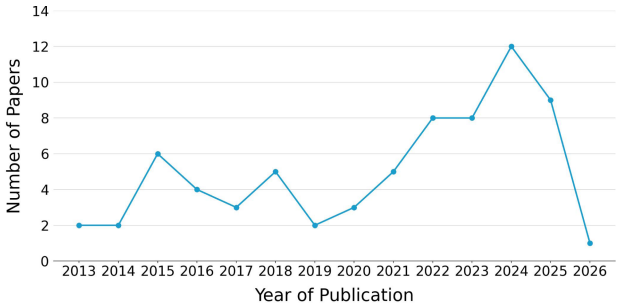


Fig. 1. Number of publications retrieved from the initial Scopus search (total: 70 publications) by year from 2013 to 2026. The figure represents the complete initial Scopus search results before screening and inclusion of the 34 functional TSA-based wearable prototype studies.

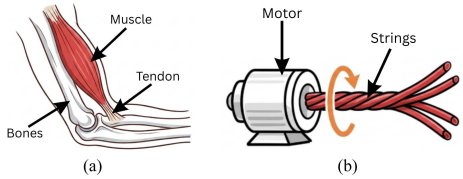


Fig. 2. Biomimetic comparison between biological actuation and TSA operation. (a) In the human arm, muscles contract via the sliding filament theory, pulling tendons to actuate joints through agonist-antagonist pairs. (b) The TSA replicates this logic: a motor twists strings to generate linear shortening and a pulling force, analogous to muscle contraction and tendon transmission respectively.

In total, 34 papers describing functional TSA-based wearable prototypes were included in this systematic review. These studies were further categorized based on anatomical application (upper limbs, trunk, or lower limbs) and primary function (haptics, assistance, augmentation, or rehabilitation). This structured classification enables a detailed comparison of key performance metrics, including force output, system weight, and degrees of freedom (DOFs), across different TSA-based wearable systems.

In addition to the selection process, a temporal analysis of the publications retrieved from Scopus was conducted to examine the evolution of research activity in TSA-based wearable systems. The distribution of documents by year, as shown in Fig. 1, indicates a generally increasing trend from 2013 to 2025, highlighting the growing interest in this field. A more pronounced rise in the number of publications can be observed after 2020, suggesting an acceleration in research and development of wearable TSA technologies. The relatively low number of publications in 2026, with only one paper identified at the time of data collection, is due to the fact that the year is still ongoing and does not yet represent a complete dataset. Therefore, this value should not be interpreted as a decline in research activity but rather as a limitation associated with the current temporal scope of the analysis. For context, a recent comprehensive review on TSA by [4] reported a total of 177 publications covering modeling, design innovations, application advances, and future challenges. In comparison, the present study identifies only 34 papers that report functional wearable TSA prototypes. This contrast highlights the gap between the broader body of TSA research and its practical implementation in wearable systems, underscoring the relatively limited number of studies that have progressed to validated, application-oriented prototypes.

II. ANATOMY-BASED CLASSIFICATION

A. Comparative Working Principles: Human Musculature Vs. TSA

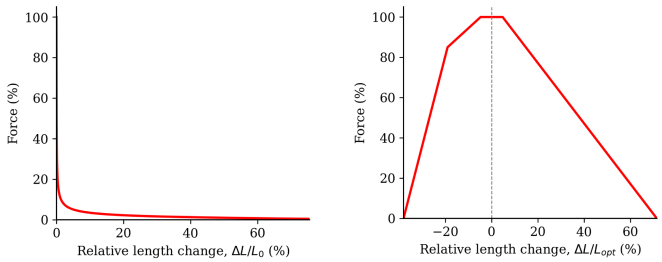
1) Qualitative Analogy TSA and Human Muscle: The integration of TSAs into wearable systems is largely driven by their biomimetic characteristics, as they closely replicate the functional dynamics of the human musculoskeletal system. In biological systems, movement is initiated by the nervous system, which sends electrical impulses to muscle fibers. According to the sliding filament theory, these signals cause actin and myosin filaments to slide past one another, resulting in a macroscopic contraction or shortening of the muscle belly. This contraction exerts a tensile force on tendons passive, fibrous connective tissues that serve as biological ‘strings‘. Because muscles are unidirectional actuators (capable only of pulling), joints are typically managed by agonist-antagonist pairs (e.g., the biceps and triceps) to achieve bidirectional rotation and stabilization [5], [6], [7].

The TSA mechanism operates on a remarkably similar mechanical logic, converting rotational energy into high-tension linear displacement. In this setup, a motor provides the rotational input, twisting a pair of high-strength strings (the mechanical equivalent of muscle fibers). As the twisting progresses, the helical geometry of the strings causes the overall length to shorten, generating a potent pulling force. Just as tendons transfer muscle contraction to the skeletal frame to actuate a joint, the contracting TSA strings pull on the structural components of the wearable device to provide assistance or augmentation [8]. This shared “contract-and-pull” principle is summarized in Table II and illustrated in Fig. 2, highlighting the synergy between human physiology and TSA-based robotic architecture.

2) Force-Displacement Behavior of the TSA and Comparison With the Muscle Force-Length Relationship: The comparison above captures the qualitative analogy between TSA

TABLE II
COMPARISON OF TSA AND HUMAN BODY EQUIVALENT

Feature	TSA	Human Body Equivalent
Primary Actuation	Motor twists strings to induce shortening	Muscles contract (Sliding Filament Theory)
Transmission	Strings convert rotation to linear motion	Tendons transfer muscle force to bone
Force Profile	Twisting increases tension and pulling force	Contraction increases tensile load on tendons
Operational Logic	Unidirectional pull (requires bias force/pair)	Agonist-Antagonist pairs for joint control



(a) (b)

Fig. 3. Both panels are plotted against the relative change in length from a reference length ($\Delta L/L_{\text{ref}}$, %) to allow direct shape comparison. Comparison between (a) the TSA force-displacement curve at constant input torque and (b) the classical skeletal muscle active force-length relationship. The TSA curve is monotonically decreasing, while the muscle curve is bell-shaped, with a two-slope ascending limb (reflecting the transition from double to single actin-filament overlap), a plateau, and a descending limb determined by actin-myosin filament overlap.

contraction and muscle contraction, but a rigorous biomimetic assessment must also examine whether the TSA reproduces one of the most defining quantitative signatures of skeletal muscle: the *active force-length relationship*. In muscle physiology, the force a muscle can actively generate is not constant but depends on its instantaneous length, following a characteristic bell-shaped curve with an ascending limb, a plateau region (optimal actin-myosin filament overlap), and a descending limb, as filament overlap increases and then decreases away from the optimal sarcomere length [9] (Fig. 3(b)).

To evaluate whether an equivalent relationship exists for the TSA, we derive the quasi-static force-displacement behavior of the actuator from its kinematic model. Following the formulation of Godler and Sonoda [10], for a TSA with $n_s = 2$ strings twisted about a motor rotation θ, with string radius r_s, offset A between the string attachment point and the TSA axis, and reference (untwisted) string length l_{0s}, the actuator contraction is given by

$$\Delta L(\theta) = l_0 - \sqrt{l_{0s}^2 - (A + r_s\theta)^2}, \tag{1}$$

where $l_0 = \sqrt{l_{0\,s}^2 - A^2}$ is the reference motor-to-load distance. Differentiating the kinematic relationship and applying the principle of virtual work under the assumption of ideal (100% efficient) mechanical transmission yields the instantaneous transmission ratio between the TSA translation velocity v and the motor angular velocity ω, which in quasi-static conditions equals the ratio between the motor torque τ_t and the output pulling force F_z:

$$\kappa(\theta) = \frac{v}{\omega} = \frac{r_s(A + r_s\theta)}{\sqrt{l_{0s}^2 - (A + r_s\theta)^2}} = \frac{\tau_t}{F_z}. \tag{2}$$

For a constant input torque τ_t, (2) can be inverted to express the output pulling force directly as a function of the twist angle,

$$F_z(\theta) = \frac{\tau_t}{\kappa(\theta)}, \tag{3}$$

which, combined with (1), defines the TSA force-displacement curve $F_z(\Delta L)$ under fixed input torque, i.e., the TSA equivalent of a muscle activated at a fixed level. As the strings twist and the actuator contracts, the transmission ratio $\kappa(\theta)$ increases monotonically, which causes the output force F_z to *decrease monotonically* with contraction at constant torque; in practice, the sharp rise predicted by (3) near $\theta \to 0$ is bounded by the motor's finite stall torque rather than growing without limit.

To illustrate this behavior quantitatively, (1)–(3) were evaluated numerically using the TSA geometric parameters reported in [4] ($r_s = 0.30$ mm, $A = 0.75$ mm, $l_{0s} = 49$ mm), under an illustrative constant input torque τ_t (not specified in [4]), selected to demonstrate the qualitative shape of the force-displacement relationship. The twist angle θ was swept from the untwisted configuration up to the onset of the geometric singularity in (2), and the resulting force values were normalized to their maximum for direct comparison with the muscle force-length curve. To enable a direct, unit-consistent comparison between the two systems addressing the mismatch between an absolute sarcomere length and a relative TSA displacement both x-axes were re-expressed as a relative length change from a reference length: $\Delta L/l_0$ (%) for the TSA, using the untwisted reference length l_0, and $\Delta L/L_{\text{opt}}$ (%) for the muscle, using the mid-plateau optimal sarcomere length L_{opt}. The sharp rise predicted near $\theta \to 0$ was capped to reflect the finite stall torque of a real actuator, analogous to the convention adopted in [4], where displacement is held constant beyond $\theta_{\max}$. Fig. 3(a) shows the resulting force-displacement curve, plotted against the corresponding relative contraction $\Delta L(\theta)/l_0$ from (1), expressed as a percentage of the reference length for direct comparison with the muscle curve in panel (b).

The comparison shows that the TSA does *not* reproduce the bell-shaped force-length relationship characteristic of muscle. Physiologically, the descending limb of the muscle curve stems from a progressive loss of actin-myosin cross-bridge overlap at supra-optimal sarcomere lengths, and the ascending limb stems from insufficient overlap at sub-optimal lengths, both molecular-scale phenomena without a mechanical analogue in string twisting. In contrast, the TSA's force decay with contraction is a purely geometric/mechanical-advantage effect: as θ increases, the helix angle grows and the transmission ratio between rotational input and translational output increases, so that a constant motor torque translates into a progressively smaller pulling force. Consequently, the TSA has no "optimal

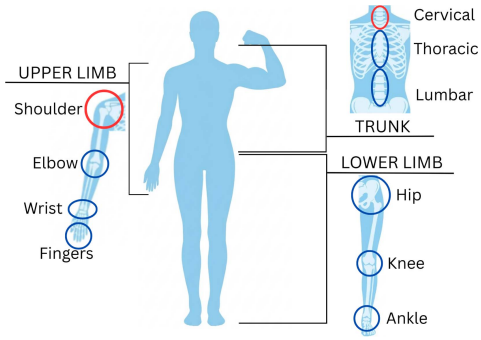


Fig. 4. Anatomical illustration highlighting principal joint regions of the human body, categorized into upper limb, trunk, and lower limb. Joints marked in red (shoulder and cervical) indicate regions where TSA-based wearable devices have not yet been reported in any literature, representing potential gaps and opportunities for future development.

length" of maximum force output analogous to the muscle's optimal sarcomere length instead, its maximum force is always obtained at or near the untwisted configuration, and it decreases as contraction proceeds toward the overtwisting limit.

To summarize, TSA reproduces the muscle's qualitative contract-and-pull actuation logic and, similarly to muscle, exhibits a load-dependent force-displacement relationship rather than a constant force output. However, the underlying mechanism and the shape of this relationship differ substantially from the muscle force-length curve: the TSA behavior is monotonic and governed by transmission-ratio kinematics (1)–(3), whereas the muscle behavior is non-monotonic and governed by molecular filament overlap. This distinction should be kept in mind when using the TSA as a biomimetic muscle-like actuator, particularly in control strategies that rely on muscle-inspired force modulation, and it defines the precise scope of the biomimetic analogy proposed in this work.

B. Anatomical Implementation of TSA-Based Wearables

TSA-based wearable devices can be systematically organized according to the anatomical segment they target. This anatomy-based classification is not merely descriptive, it directly reflects the distinct biomechanical requirements, force magnitudes, and range-of-motion constraints that govern design decisions. Three primary anatomical domains emerge from the literature: (A) the upper limb, encompassing the fingers, wrist, elbow, and shoulder (B) the trunk, covering the lumbar, thoracic, and cervical and (C) the lower limb, addressing the ankle, knee, and hip (Fig. 4). The timeline in Fig. 5 illustrates the chronological progression of device development across these three segments, and a consolidated device-level overview is provided in Table III.

1) Upper Limb. Fingers and Hand: The upper extremities require actuators that are high-precision and low-profile so as not to hinder the natural dexterity of the hand. In finger and hand applications, TSAs replicate the pulling action of human flexor tendons, routing strings along the dorsal or palmar surface of a glove substrate to drive individual finger joints. Early haptic research exemplified by the ExoTen-Glove [24] demonstrated how TSAs could render contact stiffness and grip force at the fingertips for immersive teleoperation; the minimalist Fingertip Device [22], weighing only 8.6 g, later showed that even sub-newton haptic rendering is achievable with a rigid TSA module at the fingertip level. The research focus subsequently shifted toward grip assistance and rehabilitation: the BRAG [18] and the MGlove-TS [13] target patients with weakened hand function and provide the essential flexion force needed to perform ADLs such as grasping a cup or pinching a pen, while the MO-TSA [14] extends this approach to a three-finger configuration augmented with touch sensing for more nuanced object interaction. Multi-finger dexterity is further addressed by the FLEXotendon Glove [21], which combines thumb adduction-abduction with index and middle finger flexion-extension, achieving up to 26.7 N of assistive force across tracked and compliant actuation paths. The AWARD [17] and the Hand Exoskeleton [16] complement these platforms by targeting four- and five-finger flexion-extension respectively, the latter relying on muscle sensing for intent detection rather than conventional force feedback. The Glove [12] advances the state of the art further by incorporating dual-TSA modules per finger to increase available force, achieving 17.95 N in a paired configuration, alongside IMU sensing for closed-loop rehabilitation control across all five fingers including adduction-abduction. By 2025, innovations such as the Fabric-integrated TSA-Glove [11] have further reduced bulk by weaving the TSA mechanism directly into wearable textile substrates, combining mechanical function with social discretion. Finally, the Sixth Finger [15] departs from the conventional orthotic paradigm entirely by providing a supernumerary rigid digit capable of 35.1 N of assistive force, expanding the functional workspace of users with single-hand impairment beyond what biological anatomy permits. The Active Modular Hand Orthosis [20] complements these platforms by providing flexion-extension support across multiple finger joints, bridging the boundary between hand and wrist assistance.

2) Upper Limb. Wrist: For the wrist, the literature highlights a clear trend toward multi-degree-of-freedom support that encompasses not only flexion-extension but also adduction-abduction and pronation-supination. The Compliant Robotic Wrist Orthosis [29] was among the first to demonstrate all three motion planes in a single TSA-driven device. Subsequent work, including the Smart Flexible Wrist Exoskeleton [28] and the 3-DoF Lightweight TSA Wrist Exoskeleton [27], has refined the mechanical architecture and integrated force and Inertial Measurement Units (IMU) sensing for closed-loop rehabilitation control.

3) Upper Limb. Elbow: Elbow-focused devices demonstrate that TSA systems can be both intuitive and powerful enough to support full arm movements. The Assistive Device for Arm Rehabilitation [36] and the Elbow Exoskeleton [8] are among the earliest wearable TSA implementations, establishing the feasibility of string-driven elbow flexion-extension within both soft and rigid structural frames respectively. The sEMG-Driven Soft ExoSuit [34] later incorporated surface electromyography to decode muscle activation and trigger assistance proportionally, removing the need for explicit user commands. The EMG-based Elbow Exoskeleton [32] builds on this intent-detection paradigm within a rigid frame, demonstrating that sEMG-driven control is architecture-agnostic and transferable

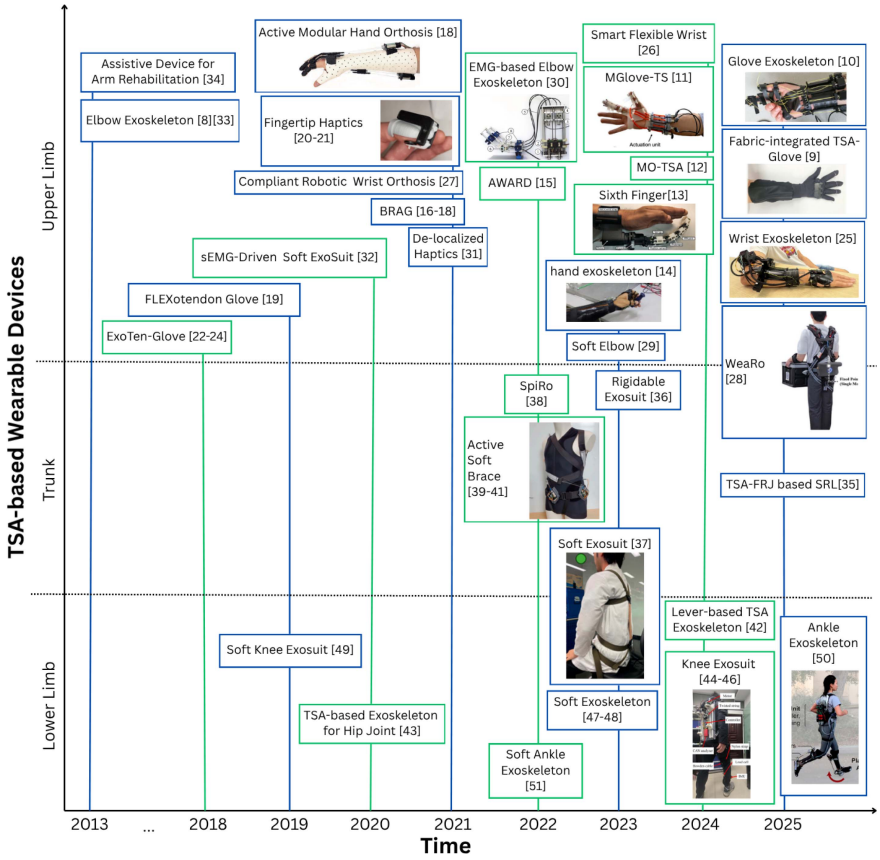


Fig. 5. Chronological development of TSA-based wearable devices identified in this review, categorized according to their primary anatomical target (upper limb, trunk, and lower limb). The timeline illustrates the evolution and diversification of TSA-based wearable prototypes from 2013 to 2025.

across structural substrates. The Soft Elbow [31] further refined structural compliance, while the WeaRo [30] extended the scope to combined arm and lumbar assistance, targeting the full kinematic chain involved in industrial handling tasks. The De-localized Haptic device [33] occupies a distinct niche within this segment, employing a rigid TSA module at the elbow not for motion assistance but to render grounded force feedback at a location spatially separated from the point of haptic interaction, demonstrating the versatility of TSA actuation beyond conventional assistive applications.

4) Trunk: The trunk serves as the biomechanical core of human physical labor, and TSA-based devices in this segment are designed primarily to prevent long-term spinal injury during sustained or repetitive exertion. The SpiRo [40] system represents a significant step forward by combining assistive and rehabilitative functions in a lumbar-thoracic orthosis: EMG and motion sensing are used to detect trunk flexion onset and activate TSA contraction in a coordinated anti-gravity strategy. The Active Soft Brace [41] addresses the lateral plane specifically, employing pressure, displacement, and stretch sensing to resist coronal-plane trunk deviations, making it particularly relevant for scoliosis rehabilitation where sagittal-plane-only support is insufficient. The Soft Exosuit [39] takes a different approach by targeting the L5/S1 junction directly through soft-knitted textile integration and sEMG feedback, reducing lumbar compressive loads during sustained forward flexion without constraining the thoracic spine. The Rigidable Exosuit [38] introduces a variable-stiffness architecture in which the normally compliant TSA substrate can be selectively stiffened on demand via IMU-triggered locking, offering a tunable balance between mobility and postural support across different task phases. The WeaRo [30] platform advances these concepts further by targeting complex industrial handling tasks, coupling lumbar support with upper-limb assistance and distributing the mechanical load across the full thoracolumbar region. Finally, the TSA-FRJ based SRL [37] departs from the conventional orthotic form factor by providing a supernumerary robotic limb anchored at the trunk, using a rigid frame and force sensing to deliver supplementary manipulation capability that offloads the upper extremities entirely during bimanual or high-load tasks.

5) Lower Limb. Hip: Lower-limb applications prioritize high torque and energy efficiency to assist with weight-bearing activities. The TSA-based Hip Exoskeleton [45] is the primary example of string-driven actuation providing auxiliary power to the hip joint during lifting tasks, distributing compressive loads that would otherwise be borne entirely by the lumbar spine and hip musculature. The Lever-based TSA Exoskeleton [44] advances this concept by incorporating a mechanical lever amplification stage between the TSA output and the hip joint, achieving a higher effective torque from the same motor while integrating sEMG, IMU, and force sensing for coordinated intent detection during dynamic lifting. The Soft Exosuit [39],

TABLE III
OVERVIEW OF TSA-BASED WEARABLE DEVICES BY ANATOMICAL SEGMENT. F/E = FLEXION-EXTENSION; AD/AB = ADDUCTION-ABDUCTION; P/S = PRONATION-SUPINATION.

Name	DoF	Available Info (Force / Weight / Sensor / Frame Type)	Application	Year	Ref.
A. Upper Limb — Fingers					
Fabric-integrated TSA-Glove	F/E (3 fingers)	+11.20% grip vs. industrial / 513g / sEMG / Soft	Assistive (grip)	2025	[11]
Glove	F/E, Ad/Ab (5 fingers)	17.95N (2 TSAs), 9.02N (TSA) / — / Force, IMU sensor / Soft	Rehabilitation	2025	[12]
MGlove-TS	F/E, Ad/Ab (5 fingers)	18N / 375g / Force sensor / Soft	Assistive, Rehabilitation	2024	[13]
MO-TSA	F/E (3 fingers)	8N / — / Touch sensor / Soft	Assistive	2024	[14]
Sixth Finger	(extra limbs)	35.1N / 170g / Force sensor / Rigid	Assistive	2024	[15]
Hand Exoskeleton	F/E (5 fingers)	— / 232g / Muscle sensor / Soft	Assistive	2023	[16]
AWARD	F/E (4 fingers)	13.55N / — / Force, displacement sensor / Soft	Assistive	2022	[17]
BRAG	F/E (5 fingers)	7N / 186g / Force & displacement sensor / Soft	Assistive (grip)	2021	[18] [19]
Active Modular Hand Orthosis	F/E (2 fingers)	— / 410g / Force sensor / Soft	Rehabilitation	2021	[20]
FLEXotendon Glove	F/E + AA (Thumb), F/E (Index, Middle)	26.7 N / — / Force, tracking, displacement sensor / Soft	Rehabilitation	2019	[21]
Fingertip Device	—	0.45 N / 8.6g / Force sensor / Rigid	Haptics	2019	[22] [23]
ExoTen-Glove	F/E (5 fingers)	80N / 360g / Force sensor / Soft	Haptic	2018	[24] [25] [26]
A. Upper Limb — Wrist					
Lightweight Flexible TSAs-Based Wrist Exoskeleton	F/E, Ad/Ab, P/S	— / — / IMU / Soft	Rehabilitation	2025	[27]
Smart Flexible Wrist Exoskeleton	F/E, Ad/Ab, P/S	— / — / Force & IMU / Soft	Rehabilitation	2024	[28]
Compliant Robotic Wrist Orthosis	F/E, Ad/Ab, P/S	— / — / Position sensor / Soft	Rehabilitation	2021	[29]
A. Upper Limb — Elbow					
WeaRo	F/E	— / 5.2kg / EMG, IMU / Soft	Assistive (handling)	2025	[30]
Soft Elbow	F/E	— / — / sEMG, IMU / Soft	Assistive	2023	[31]
EMG-based Elbow Exoskeleton	F/E	— / — / sEMG / Rigid	Rehabilitation	2022	[32]
De-localized Haptic	—	— / — / Force sensor / Rigid	Haptic	2021	[33]
sEMG-Driven Soft ExoSuit	F/E	— / — / Force & sEMG / Soft	Assistive	2020	[34]
Elbow Exoskeleton	F/E	— / 2.2 kg / Linear displacement sensor / Rigid	Experimental	2013	[8] [35]
Assistive Device for Arm Rehabilitation	F/E	— / — / — / Rigid	Assistive	2013	[36]
B. Trunk					
TSA-FRJ based SRL	(extra limbs)	— / 3.5kg / Force sensor / Rigid	Assistive	2025	[37]
WeaRo	F/E (Lumbar)	— / 5.2kg / EMG, IMU / Soft	Assistive (handling)	2025	[30]
Rigidable Exosuit	F/E, Lateral Flexion, Rotation (Lumbar, Thoracic)	— / — / IMU / Soft	Assistive	2023	[38]
Soft Exosuit	F/E (Lumbar)	— / — / Soft Knitting, sEMG / Soft	Assistive (Spinal)	2023	[39]
SpiRo	F/E (Lumbar, Thoracic)	— / — / EMG & Motion sensor / Rigid	Assistive, Rehabilitation	2022	[40]
Active Soft Brace	Lateral, Rotation (Lumbar, Thoracic)	— / — / Pressure, Displacement, Stretch / Soft	Rehabilitation	2022	[41] [42] [43]
C. Lower Limb — Hip					
Lever-based TSA Exoskeleton	F/E	— / — / sEMG, IMU, Force / Rigid	Augmentation (lifting)	2024	[44]
Soft Exosuit	F/E	— / — / Soft Knitting, sEMG / Soft	Assistive (Spinal)	2023	[39]
TSA-based Exoskeleton for Hip Joint Assistance	F/E	— / — / Force sensor / Rigid	Assistive/Augmentation	2020	[45]
C. Lower Limb — Knee					
Knee Exosuit	F/E	— / — / EMG, IMU / Rigid	Assistive (walking)	2024	[46] [47]
Soft Exoskeleton	F/E	— / — / sEMG, IMU / Soft	Assistive (walking)	2023	[48] [49]
Soft Knee Exosuit	F/E	— / 3.5kg / IMU, pull-wire placement sensor / Soft	Assistive (climbing)	2019	[50]
C. Lower Limb — Ankle					
Ankle Exoskeleton	Plantar Flexion	— / 3.5 kg / Force sensor / Rigid	Assistive (Running)	2025	[51]
Soft Ankle Exoskeleton	Plantar Flexion	— / — / — / Soft	Rehabilitation	2022	[52]

which also appears in the trunk segment, provides simultaneous hip and lumbar assistance through a continuous soft-knitted garment, demonstrating that multi-joint coverage across anatomically adjacent segments is achievable within a single TSA-driven platform. Across all three devices, the core design challenge remains consistent: routing string conduits along the thigh without impeding the full range of hip flexion-extension during locomotion.

6) Lower Limb. Knee: In the knee segment, the Soft Knee Exosuit [50] remains a benchmark for specialized TSA-based assistance, specifically targeting climbing activities in which the actuator's high gear-reduction ratio delivers the large knee extension torques required. More recent developments, such as the Soft Exoskeleton [48], have broadened the scope to general walking assistance, employing sEMG and IMU sensors to synchronize TSA contraction with the gait cycle and thereby reduce the metabolic cost of locomotion for elderly users or those recovering from orthopedic injury. The Knee Exosuit [46] extends this walking-assistance paradigm into a hybrid rigid-frame architecture, retaining joint-axis alignment through a structural knee brace while relying entirely on TSA strings for force transmission, with fused EMG and IMU signals driving the intent-detection layer.

7) Lower Limb. Ankle: The ankle represents the most recently addressed lower-limb segment within the TSA wearable literature. The Ankle Exoskeleton [51] targets plantar flexion assistance during running, employing a rigid structural frame grounded at the shank and a force-sensed TSA transmission to deliver timely push-off augmentation synchronized with the running gait cycle; at 3.5 kg, it occupies the heavier end of the reviewed device spectrum, reflecting the high output forces demanded by running biomechanics. The Soft Ankle Exoskeleton [52] addresses the rehabilitation context with a contrasting design philosophy: a fully soft substrate that conforms to the ankle-foot complex without constraining the joint axis, prioritizing compliance and comfort for clinical populations undergoing plantar flexion recovery. Together, these two devices establish the initial boundaries of TSA-based ankle assistance, though the broader ankle-foot complex, including dorsiflexion support and foot drop correction, remains a largely open design space within the TSA literature.

III. MECHANICAL DESIGN AND CONTROL

The mechanical design of a TSA-based wearable system involves a cascade of interdependent decisions that span actuator configuration, structural architecture, force transmission strategy, and sensing modality. These choices are tightly coupled: a decision to increase the number of actuated degrees of freedom inevitably affects system weight, routing complexity, and control bandwidth. This section examines the dominant design patterns that have emerged across the reviewed literature.

A. Actuator Configuration and Force Transmission

TSA converts the rotary motion of a DC motor into linear contraction by twisting a pair (or bundle) of strings wound around

the motor shaft. As the motor rotates, the strings intertwine, reducing their effective length and generating a pulling force on the attached load. This mechanism is inherently backdrivable at low loads, lightweight, and mechanically simple, making it well suited for wearable applications where mass and profile are primary constraints.

The key design parameters of a TSA are string material, string diameter, initial string length, and the number of strands. Longer strings produce greater stroke at the cost of slower response; thinner strings reduce mass but lower the maximum transmissible force. In practice, reviewed devices have achieved assistive forces ranging from 7 N in early grip-assistance gloves [18] to 80 N in haptic finger exoskeletons [24], with the MGlove-TS reaching 18 N across five fingers simultaneously [13]. Force output is further modulated by the gear ratio of the driving motor and, critically, by the non-linear contraction kinematics of the TSA: contraction rate and output force both vary with the instantaneous twist angle, requiring compensation in the control law.

Routing strategy determines how the linear stroke generated by each TSA module is transferred to the target joint. Two approaches dominate. In *direct routing*, the string exits the motor spool and attaches directly to a rigid cuff or fingertip thimble, maintaining a short, low-friction path. This approach is used in most finger and wrist devices, where the joint and the actuator module can be co-located on the dorsum of the hand. In *tendon routing*, the string is guided through low-friction sheaths or pulleys to reach a remote attachment point, enabling the motor to be placed proximally on the forearm or torso to reduce distal mass. The WeaRo exosuit [30], for example, mounts all motors at the trunk and routes tendons distally to the arm and lumbar region, keeping the total device weight at 5.2 kg while covering multiple joints. Tendon routing introduces friction and hysteresis that must be accounted for in force estimation.

The placement of TSA modules embedded in the substrate versus externally mounted represents a further design trade-off. Embedded actuators, as in the Fabric-integrated TSA-Glove [11], reduce snag risk and improve wearability but complicate maintenance and replacement. External modules allow modular reconfiguration across tasks but increase the overall system profile.

B. Degrees of Freedom

The number of actuated DoFs varies considerably across the reviewed devices, from single-DoF supports to five-DoF hand exoskeletons. At the minimal end, devices such as the Soft Knee Exosuit [50], the Ankle Exoskeleton [51], the Soft Ankle Exoskeleton [52], and all elbow-segment devices including the sEMG-Driven Soft ExoSuit [34], the Soft Elbow [31], the EMG-based Elbow Exoskeleton [32], and the WeaRo [30] target a single flexion-extension axis, simplifying routing and control at the cost of functional coverage. Hip devices including the TSA-based Hip Exoskeleton [45] and the Lever-based TSA Exoskeleton [44] similarly restrict actuation to the sagittal plane, reflecting the dominant mechanical demand of lifting and locomotion tasks. Trunk devices such as the SpiRo [40], the Soft Exosuit [39], and the Rigidable Exosuit [38] address flexion-extension of the lumbar spine, while the Active Soft Brace [41] uniquely targets the lateral (coronal) plane. At the opposite extreme, multi-DoF wrist devices the Compliant Robotic Wrist Orthosis [29], the Smart Flexible Wrist Exoskeleton [28], and the Lightweight Flexible TSA Wrist Exoskeleton [27], each actuate three independent axes: flexion-extension, adduction-abduction, and pronation-supination. Hand exoskeletons span the widest range: the Active Modular Hand Orthosis [20] covers two fingers, the MO-TSA [14] and Fabric-integrated TSA-Glove [11] address three, the AWARD [17] targets four, and the ExoTen-Glove [24], BRAG [18], Hand Exoskeleton [16], and Glove [12] extend to all five. The FLEXotendon Glove [21] and MGlove-TS [13] further incorporate adduction-abduction at the thumb and inter-finger axes respectively, approaching the full kinematic complexity of the human hand. Multi-DoF systems require careful mechanical routing to ensure that individual string paths remain independent and do not cross-couple joint torques, typically addressed through finger-specific routing channels embedded in a glove substrate with each TSA module assigned to one motion axis.

C. Sensing and State Estimation

Effective control of TSA-based wearables requires knowledge of the device state and the user's intent. The following sensing modalities are represented in the reviewed literature:

Proprioceptive sensing encompasses motor encoders and string displacement sensors that track actuator state. In the TSA, the relationship between motor angle and string contraction is non-linear; therefore, several works have incorporated lookup tables or real-time kinematic solvers to estimate end-effector displacement from motor position alone. Displacement sensing is a core feedback element in the BRAG [18], the FLEXotendon Glove [21], the AWARD [17], and the Elbow Exoskeleton [8], where linear displacement sensors provide direct observation of string contraction independently of the motor angle.

Inertial Measurement Units (IMUs) are widely used to estimate joint angles and trunk orientation without the need for rigid kinematic linkages. Their lightweight and low-power characteristics make them well suited for wearable integration, and they appear across a wide range of reviewed devices including the Smart Flexible Wrist Exoskeleton [28], the Lightweight Flexible TSA Wrist Exoskeleton [27], the Soft Knee Exosuit [50], the Glove [12], the SpiRo [40], the Rigidable Exosuit [38], the WeaRo [30], the Soft Elbow [31], the Lever-based TSA Exoskeleton [44], the Soft Exoskeleton [48], and the Knee Exosuit [46]. Magnetic disturbances and drift accumulation remain practical limitations common to all IMU-based implementations.

Surface electromyography (sEMG) provides a direct window into the user's motor intent by recording the electrical activity of superficial muscles before mechanical movement occurs. Its use as a feedforward control signal as demonstrated in the sEMG-Driven Soft ExoSuit [34] enables proactive assistance that is temporally synchronized with user intention rather than lagging behind it. sEMG is similarly employed in the Fabric-integrated

TSA-Glove [11], the Soft Elbow [31], the WeaRo [30], the SpiRo [40], the Soft Exosuit [39], the Lever-based TSA Exoskeleton [44], the Soft Exoskeleton [48], the Knee Exosuit [46], and the EMG-based Elbow Exoskeleton [32]. The Hand Exoskeleton [16] employs a generalized muscle sensor rather than surface electrodes, offering an alternative acquisition strategy for hand muscles where electrode placement is anatomically constrained. Challenges shared across all sEMG implementations include electrode placement sensitivity, sweat-induced signal degradation, and the need for per-session calibration.

Force and pressure sensors are employed at the human-device interface to measure the interaction forces between the user and the exoskeleton. These signals are essential for impedance and admittance control schemes, ensuring that the device does not apply forces that conflict with the user's voluntary effort. Force sensing is a central feedback element across a broad range of devices spanning all anatomical segments. In the finger and hand segment, reported output forces vary considerably with device purpose and scale: the Fingertip Device [22] renders 0.45 N of cutaneous feedback from an 8.6 g module, the BRAG [18] delivers 7 N of grip assistance across five fingers, the MO-TSA [14] provides 8 N across a three-finger configuration, the AWARD [17] achieves 13.55 N over four fingers, the Glove [12] generates 9.02 N per single TSA and 17.95 N in its dual-TSA configuration, the MGlove-TS [13] reaches 18 N across all five fingers simultaneously, the FLEXotendon Glove [21] produces 26.7 N across the actuated thumb and finger axes, the Sixth Finger [15] delivers 35.1 N through its rigid supernumerary digit, and the ExoTen-Glove [24] achieves 80 N at the fingertips for high-fidelity haptic rendering. Force sensing is equally present in devices for which output force values were not reported, including the Active Modular Hand Orthosis [20], the De-localized Haptic device [33], the Hip Exoskeleton [45], the Lever-based TSA Exoskeleton [44], the TSA-FRJ based SRL [37], and the Ankle Exoskeleton [51], where it serves primarily as a closed-loop safety and control signal rather than a characterization metric. The Active Soft Brace [41] extends the sensing palette further by incorporating pressure, displacement, and stretch sensors simultaneously, providing a multi-modal picture of coronal-plane trunk loading that no single transducer type could capture alone.

D. Structural Substrates

Wearable exoskeletons are broadly classified into three structural categories: rigid, soft, and hybrid. Rigid exoskeletons provide strong structural support and precise kinematic control but tend to be heavier and expensive, owing to their construction from materials such as Polylactic Acid (PLA), metal, or carbon fibre. They are designed for tasks requiring greater strength and stability, making them well suited for rehabilitation and augmentation applications. Soft exoskeletons prioritise comfort and flexibility through the use of lighter, compliant materials such as textiles or polymers. They offer less mechanical force output but greater adaptability to the human body, and are generally more breathable and comfortable for prolonged use making them especially beneficial for assistive applications. Hybrid exoskeletons occupy the middle ground: they employ a rigid structural frame for mechanical support while relying on a soft actuation system to transmit force, balancing flexibility with structural stability [53].

Because all devices surveyed in this review employ TSA, the actuation mechanism is inherently soft and string-based in every case. A TSA generates force through the contraction of twisted strings driven by a compact motor, with no rigid transmission elements such as gears or linkages between the motor and the load. This means that *no device in this survey can be classified as fully rigid:* the moment a TSA is adopted as the actuation strategy, the system acquires at least one inherently soft and compliant force-transmission pathway. The relevant structural distinction across the reviewed literature is therefore not rigid versus soft, but rather *soft versus hybrid* where soft devices pair a textile or silicone substrate with TSA actuation, and hybrid devices pair a rigid structural frame with the same soft TSA actuation.

Soft-substrate devices combine a conformable textile or silicone base layer with TSA strings routed along or through the garment and anchored at sewn attachment points or cuffs. Because there is no external joint structure, these devices are inherently tolerant of anatomical variation across users and postures, and they impose minimal restriction on degrees of freedom that are not being actively assisted. The majority of devices reviewed including the MGlove-TS [13], the Fabric-integrated TSA-Glove [11], the sEMG-Driven Soft ExoSuit [34], and the Soft Knee Exosuit [50] fall into this category. The dominant limitation is compliance-induced uncertainty: a soft substrate deforms under load, making the relationship between string contraction and joint angle non-linear, posture-dependent, and sensitive to donning tightness. Closed-loop sensing is therefore required to observe the output state independently of the actuator. A further concern is anchor slippage: if the garment shifts under the TSA reaction force, the effective moment arm changes unpredictably, requiring either mechanically stiff embedded anchor zones or adaptive control compensation.

Hybrid devices retain a rigid structural frame to constrain the assisted joint axis and ground the TSA reaction forces predictably, while the actuation itself remains soft through the use of twisted strings. This is precisely the definition of a hybrid exoskeleton: a hard material for structural support combined with a soft material actuator for the actuation system. The rigid frame recovers the kinematic predictability of a conventional exoskeleton, the mechanical advantage of the TSA at the joint can be computed analytically and remains stable across postures, while the string transmission preserves the low mass and mechanical simplicity that distinguish TSA-based designs from motor-and-gearbox alternatives. The Assistive Device for Arm Rehabilitation [36] and the Elbow Exoskeleton [8] are representative examples, constraining motion to a single flexion-extension axis through a rigid linkage while using TSA strings as the sole force-transmission element.

Table III reflects this distribution clearly: rigid-frame (hybrid) constructions are concentrated in elbow and wrist devices where joint axis alignment is biomechanically critical, while fully soft substrates dominate hand, knee, and trunk applications where

conformability and low weight take priority. The progressive shift toward soft and hybrid architectures from 2021 onward is consistent with the broader wearable robotics literature, in which user acceptance studies have repeatedly identified device weight, bulkiness, and donning difficulty as primary barriers to clinical adoption, factors that the inherent softness of TSA actuation directly addresses, regardless of whether the structural substrate is textile or rigid.

E. Control Challenge

The TSA's non-linear force-displacement relationship is the primary control challenge shared across all reviewed devices. Because the string contraction rate and output force both depend on the instantaneous twist angle, a constant motor velocity produces a decreasing contraction speed over time. Accurate force or position control therefore requires either a model-based compensator or an outer feedback loop from a force or displacement sensor.

A second challenge arises from the backdrivability of soft substrates. Unlike rigid exoskeletons with well-defined kinematics, soft wearables exhibit compliance at the human-device interface that varies with limb posture, garment fit, and user anatomy. This makes it difficult to predict the effective mechanical advantage at the joint from actuator state alone, motivating the use of redundant sensing (e.g., IMU plus sEMG) to close the control loop from the output side rather than relying exclusively on motor-side measurements.

Intent detection adds a further layer of complexity in assistive applications. Threshold-based sEMG triggers are simple to implement but susceptible to noise and inter-session variability. More robust approaches combine sEMG with kinematic cues, for example, the WeaRo controller fuses EMG and IMU signals to distinguish task-relevant arm motions from incidental movement [30], but this increases the computational load and the calibration burden on the user. Rehabilitation applications face an additional requirement: the control law must modulate assistance as a function of patient recovery progress, demanding adaptive or patient-in-the-loop control architectures that remain an open research problem across the reviewed literature.

F. Limitations and System-Level Trade-Offs

While the preceding sections establish the mechanical versatility of TSA-based wearables, a critical assessment of the technology's limitations relative to conventional geared transmissions is necessary to contextualize its future development trajectory, revisiting the comparative framework introduced in Table I.

a) Efficiency: Reported transmission efficiencies for TSAs vary considerably with load, twist angle, and string configuration. Single-string TSAs operating under steady load have been measured at efficiencies approaching 90% [54], comparable to or better than the approximately 60% reported for high-reduction-ratio planetary gearsets and the 70–80% typical of harmonic or cycloid drives [55]. Unlike a gearbox, whose efficiency curve is largely load-independent and characterized once at the design stage, TSA efficiency is coupled to the instantaneous twist angle and degrades non-uniformly as the actuator approaches the overtwisting limit discussed in Section I-A. This makes TSA efficiency harder to guarantee across the full operating range of a wearable device, even where its best-case performance is competitive with geared alternatives.

b) Weight and system-level footprint: At the joint, TSA offers a clear weight advantage: Table III shows device masses as low as a few hundred grams for finger- and hand-level devices, an order of magnitude below what a comparable geared actuator would require at the same output force. However, this advantage is partly illusory at the system level: TSA requires either a co-located motor (adding local mass back) or remote placement with tendon routing, which introduces sheath friction, hysteresis, and routing complexity, as discussed for the WeaRo exosuit [30] in Section I-A. A fair weight comparison must therefore account for the full drivetrain, not just the joint-side mass.

c) Complexity and cost: Mechanically, TSA is simpler and cheaper than a precision gearbox: it has no meshing teeth, requires no lubrication, and can be manufactured from low-cost, off-the-shelf string material, which likely contributes to its attractiveness for research prototypes and low-cost assistive devices. This simplicity comes at the cost of control complexity, however, since the non-linear force-displacement relationship (Section I-A, (1)–(3)) demands either a model-based compensator or closed-loop sensing that a geared actuator with near-linear kinematics does not require. String durability is a further and largely unquantified cost factor: unlike metal gear teeth, strings are subject to progressive wear, fraying, and eventual failure under cyclic loading, and none of the reviewed devices report long-term fatigue or replacement-interval data, leaving the effective lifecycle cost of a TSA-based device an open question for clinical or industrial deployment.

d) Net assessment: Relative to harmonic or planetary geared actuation, TSA trades a well-characterized, load-independent efficiency and linear transmission for lower joint-side weight, lower cost, and higher intrinsic compliance, at the expense of non-linear kinematics, load-dependent efficiency, and unresolved long-term durability. This positions TSA not as a strictly superior actuation technology but as the preferred choice specifically in applications, such as the compact, low-power wearable devices surveyed in this review, where joint-side mass and compliance dominate the design requirements over peak efficiency and long-term mechanical predictability.

IV. Control Algorithm

The control architecture of a TSA-based wearable device governs how the actuator interacts with the human body, how assistive forces are generated and regulated, and how the system responds to voluntary user effort. Across the literature, control strategies can be broadly divided into two fundamental categories: active interaction control, in which onboard sensing and real-time computation continuously modulate the actuator output, and passive interaction control, in which the mechanical compliance of the transmission itself governs the force-motion relationship without closed-loop intervention. Most practical

TSA-based wearables adopt one of these paradigms or combine elements of both within a layered architecture.

1) Active Interaction Control: Active interaction control relies on sensors, actuators, and real-time feedback loops to continuously regulate the forces and motions exchanged at the human-robot interface. The controller monitors one or more physical quantities, such as joint position, interaction force, muscle activation, or inertial orientation and adjusts motor commands accordingly, enabling the device to adapt dynamically to the user's intent and the mechanical demands of the task.

The majority of TSA-based wearables surveyed in Table III operate under active control schemes. Position-based strategies, in which motor shaft angle is regulated to track a desired string displacement and thereby prescribe joint motion, are predominant in rehabilitation-oriented devices where a repeatable trajectory must be enforced. The Compliant Robotic Wrist Orthosis [29], the Smart Flexible Wrist Exoskeleton [28], and the 3-DoF Lightweight TSA Wrist Exoskeleton [27] exemplify this approach, augmenting position feedback with IMU sensing to close the loop over joint-space coordinates rather than motor-space coordinates. Force and torque control strategies, which directly regulate the interaction force at the human-robot interface via dedicated in-series sensors, are employed where safety margins or task-proportional assistance must be explicitly enforced: the ExoTen-Glove [24] and the Fabric-integrated TSA-Glove [11] regulate fingertip contact force for haptic rendering and grip assistance respectively, while the Hip Exoskeleton [45] modulates joint-level torque in proportion to the measured load during lifting. Intent-driven strategies, which infer voluntary effort from sEMG or IMU signals and use this estimate to trigger or scale TSA contraction, are prevalent in assistive devices targeting naturalistic daily activities: the sEMG-Driven Soft ExoSuit [34], the Soft Elbow [31], the WeaRo [30], and the SpiRo [40] all adopt variants of this approach across elbow, arm, and trunk segments.

2) Passive Interaction Control: Passive interaction control manages the human-robot interface through mechanical design alone, without real-time computational force modulation. Compliance is instead built into the transmission or structural elements of the device through springs, elastic substrates, or the inherent backdrivability of the TSA mechanism itself, so that the device yields to external forces in a physically stable and energetically passive manner. This approach is inherently safe, since a passive system can only store or dissipate energy and cannot inject destabilizing forces into the interaction. Passive control has no user intent detection, has minimal to no sensor, and works as mechanical support rather than powered or adaptive assistant. The complexity is also low, like in elbow exoskeleton [8]. Passive control strategies are therefore not merely a design simplification but a deliberate safety and comfort mechanism.

V. Application Area

The TSA mechanism is not merely a product of modern soft robotics, its fundamental mechanical principles have been utilized since antiquity to actuate early technological systems. Historically, the storage and release of energy through twisted fibers were foundational to the development of torsion siege engines, such as catapults, and primitive machining tools like pump drills. As documented by Gaponov et al. [8], these ancient applications laid the groundwork for understanding how torsional strain can be converted into linear displacement a principle that remains the core of modern TSA research.

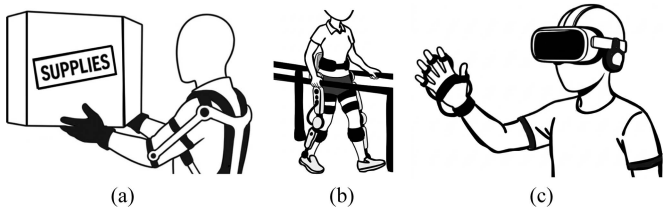


Fig. 6. Examples of wearable devices across three application domains: (a) augmentation: a robotic exoskeleton suit aiding a person in lifting and carrying heavy supplies, (b) rehabilitation: a lower-limb exoskeleton supporting a patient in relearning walking motion using parallel bars, and (c) haptics: a user equipped with a VR headset and haptic glove interacting with a virtual environment through simulated touch feedback.

With the contemporary shift toward compliant and lightweight robotic systems, these ancient mechanical concepts have been reimagined through the lens of modern materials science. The evolution from rigid, heavy-duty siege engines to miniaturized, bio-compatible wearable actuators represents a significant paradigm shift in engineering. As illustrated in Fig. 6, TSA-based wearable systems have been explored across a broad range of applications, including haptic feedback, human augmentation, assistive technologies, and rehabilitation. As categorized in Table II, modern TSA-based wearables now serve a dual purpose: they bridge the gap between human biological capabilities and mechanical assistance, offering versatile solutions for both healthy individuals and those suffering from physical impairments.

A. Augmentation

Human augmentation represents the most prominent application domain for TSA-based wearable devices. These systems are specifically engineered to enhance the physical performance of healthy users such as hikers, climbers, or industrial workers who operate in high-exertion environments [56] By providing supplementary force during strenuous activities, TSA-based wearable devices allow users to exceed their natural physiological limits while maintaining a high degree of mobility [57]. Unlike traditional electric motors, the compliance of TSAs ensures that the augmentation is "bio-inspired," moving in harmony with the user's natural musculoskeletal structure rather than resisting it.

In industrial and military sectors [58], the primary objective of augmentation is the mitigation of both acute and chronic injuries. Workers frequently engage in repetitive tasks, such as overhead reaching or heavy lifting, which lead to minor ailments like muscle fatigue and tendon strain [59]. Over time, these can escalate into severe musculoskeletal disorders, including spinal compression or ligament tears.A significant trend in recent literature is the development of lumbar and knee assistance systems for lifting and climbing tasks. For example, the Soft

Knee Exosuit [50] was specifically designed to provide climbing assistance, while the TSA-based Exoskeleton for Hip Joint Assistance [45] aims to alleviate the physical burden during heavy lifting tasks. More recently, the WeaRo system [30] has emerged as a state-of-the-art solution for general handling task assistance, demonstrating the technology's evolving maturity in supporting complex industrial workflows. These devices not only enhance endurance but also serve a critical protective role by reducing the risk of chronic spinal compression and ligament injuries.

B. Assistive

While augmentation focuses on performance enhancement, assistive applications are dedicated to restoring autonomy in performing ADLs. As the global population ages, there is an increasing demand for technologies that compensate for the natural decline in muscle mass and joint stability. TSA-based wearables provide the necessary torque to assist in fundamental movements, such as standing from a seated position or grasping objects. Because TSAs are inherently "soft" and lightweight, they are uniquely suited for elderly users who may find traditional, rigid exoskeleton frames too heavy or intimidating to use in a domestic setting [60].

Furthermore, these devices offer transformative potential for individuals living with permanent physical disabilities. By providing active assistance, TSA-based systems enable users to perform essential tasks such as eating, opening doors, or navigating stairs without the constant need for a human caregiver. The primary goal is to improve the overall quality of life by expanding the user's range of motion and functional independence. The low profile of TSA mechanisms also ensure that these devices are socially discrete, reducing the stigma often associated with bulky assistive hardware [61].

Recent breakthroughs have focused heavily on Assistive Gloves and upper-limb support to facilitate ADLs. Devices such as the BRAG [18] and the Fabric-integrated TSA-Glove [11] provide crucial grip assistance, enabling users to perform simple tasks like opening doors or eating with minimal effort. Furthermore, the sEMG-Driven Soft ExoSuit [34] utilizes electromyography signals to provide intuitive elbow flexion-extension assistance, bridging the gap between user intent and mechanical support. These technologies empower users with disabilities to expand their range of motion and maintain independence without relying on constant caregiver intervention.

C. Rehabilitation

The lightweight and high-efficiency characteristics of TSAs have established them as a cornerstone of modern clinical rehabilitation. Traditional rehabilitation robots are often massive, stationary machines that require patients to travel to a clinic. In contrast, TSA-based wearables are compact and portable, facilitating the transition toward home-based telerehabilitation. These devices provide stable, repeatable, and controllable resistance or assistance, which is critical for neuroplasticity and muscle recovery following strokes or traumatic injuries [62], [63].

A representative example of this innovation is the Wrist Exoskeleton designed by Dragunasu et al. [27]. This system incorporates a sophisticated "learning mode" that allows it to follow a precise movement profile pre-recorded by a physical therapist. This capability ensures that the rehabilitation process is tailored to the specific anatomical needs of the patient. By providing consistent, high-fidelity mechanical feedback, TSA-based systems help patients regain motor control faster and more effectively than through manual therapy alone. The Smart Flexible Wrist Exoskeleton [28] and the 3 DoF Lightweight Flexible Exoskeleton [27] both provide comprehensive support for flexion-extension, adduction-abduction, and pronation-supination. These devices often feature "learning mode" where the exoskeleton can replicate precise therapeutic profiles established by clinicians. Additionally, the MGlove-TS [13] serves a dual purpose in both assistance and rehabilitation, highlighting the versatility of TSA-based hand orthoses in treating chronic hand dysfunction.

D. Haptics

Beyond physical assistance, augmentation, and rehabilitation, TSA technology is increasingly being integrated into advanced haptic interfaces. These devices are designed to simulate the sense of touch in Virtual Reality (VR) environments or during the remote operation of robotic systems (teleoperation). Because TSAs can generate significant tension within a very small footprint, they are ideal for integration into wearable gloves or sleeves where space is at a premium. They provide the "force feedback" necessary for a user to "feel" the weight or resistance of a virtual object, creating a truly immersive experience [64].

The ExoTen-Glove [24] remains the hallmark example of this application: by contracting TSA strings routed to the fingertips, the glove simulates the stiffness of different materials or the grip force required to hold a virtual object, with 80 N of available fingertip force providing a wide dynamic range for rendering both delicate and rigid contact events. The Fingertip Device [22] pursues the same objective in a radically miniaturized form: at 8.6 g and 0.45 N of output force, it demonstrates that meaningful cutaneous haptic rendering is achievable with a single rigid TSA module attached to one fingertip, opening the door to ultra-low-profile haptic thimbles that can be worn unobtrusively during extended VR interaction. The De-localized Haptic device [33] introduces a conceptually distinct approach: rather than rendering force at the fingertip or hand, it applies a grounded reaction force at the elbow via a rigid TSA module, creating the perceptual illusion of a contact event at a spatially remote location. This de-localization principle is particularly relevant for upper-limb prosthetics and teleoperation scenarios in which the true contact site is inaccessible to a conventional wearable haptic interface.

VI. Perspective

The findings of this systematic review point toward several promising yet underexplored directions that will shape the next generation of TSA-based wearable research. These future opportunities are organized below according to four thematic dimensions: anatomical coverage, technical open problems, sensing and intent detection, and system-level integration.

a) Anatomical Gaps: Despite the breadth of anatomical coverage documented in this review, two major body segments remain conspicuously absent from the TSA wearable literature: the shoulder and cervical complex. The shoulder and cervical joint is among the most injury-prone regions in both industrial and sports contexts, yet it presents a unique engineering challenge due to its complex multi-degree-of-freedom ball-and-socket geometry, which complicates TSA string routing and anchor point definition. The absence of any shoulder and cervical targeted TSA device in the reviewed literature is therefore not a reflection of limited clinical need, but rather of unresolved mechanical design challenges that represent a high-priority direction for future work.

b) Technical Open Problems: Several fundamental technical challenges persist across the reviewed literature. The inherent non-linearity of TSA kinematics remains a primary control obstacle: as the instantaneous twist angle evolves during actuation, both the contraction rate and the output force vary in a coupled, non-linear manner that existing analytical compensators only partially address. Future work should investigate learned or adaptive compensators, including model-free machine learning approaches, capable of capturing these dynamics across diverse operating conditions and user anatomies without requiring precise physical models. A second and largely overlooked concern is the mechanical degradation of strings under prolonged cyclic loading. Across the reviewed devices, long-term durability data are almost entirely absent, yet string wear and fatigue are critical factors for clinical adoption, where a device must function reliably over months of daily use without requiring frequent maintenance or string replacement. Addressing this gap will require standardized accelerated aging protocols and the systematic evaluation of candidate string materials under realistic loading conditions. A third systemic limitation is the predominance of laboratory-based validation with healthy subjects. Real-world deployment with clinical populations, who present irregular movement patterns, muscle weakness, and co-morbidities, remains largely unexplored and represents an essential step toward the translational readiness of TSA-based wearable technology.

c) Bilateral and Full-Body Integration: The vast majority of reviewed devices target a single joint or limb segment in isolation, whereas real-world physical tasks inherently involve coordinated multi-joint motion spanning the full kinematic chain. Platforms such as WeaRo [30] represent early and significant steps toward full-body coverage by coupling lumbar and upper-limb assistance within a single wearable system. The Soft Exosuit [39] similarly spans multiple segments by simultaneously addressing the L5/S1 junction and the hip joint through a continuous soft-knitted garment, demonstrating that a single TSA-driven platform can distribute load reduction across anatomically adjacent regions without requiring separate devices. The TSA-FRJ based SRL [37] pushes this concept further by anchoring a supernumerary robotic limb at the trunk and routing TSA actuation to an independent rigid manipulator, decoupling the augmentation function entirely from the biological skeleton and enabling whole-body task strategies that involve the supernumerary limb as an active participant. However, simultaneously coordinating TSA modules across the shoulder, elbow, wrist, and fingers or across the hip, knee, and ankle introduces inter-joint coupling effects and shared control bandwidth constraints that existing architectures such as those in the Knee Exosuit [46] or the Lever-based TSA Exoskeleton [44] are not yet equipped to handle in combination. Developing unified, multi-segment control frameworks that account for these mechanical couplings while preserving the lightweight and compliant character of TSA actuation remains a high-impact research direction. The Rigidable Exosuit [38] offers a partial solution in the trunk segment by introducing variable stiffness as a mode-switching mechanism, but extending this concept across a full kinematic chain with dynamically varying task demands remains an open and defining challenge for the next generation of TSA-based wearable platforms.

VII. Conclusion

This systematic review has provided a comprehensive analysis of the current state of the art in TSA-based wearable devices, surveying the literature across three primary anatomical domains: the upper limb, the trunk, and the lower limb, and four functional application categories: augmentation, assistive technology, rehabilitation, and haptics. The findings reveal that upper limb devices, particularly those targeting the fingers and wrist, dominate the reviewed literature, reflecting the research community's sustained focus on hand rehabilitation and dexterous haptic interaction. Trunk and lower limb systems, while fewer in number, have grown considerably in sophistication over the review period, as demonstrated by the multi-segment WeaRo [30] platform.

A clear and consistent design trend was identified across the reviewed timeline: a progressive shift away from rigid structural substrates toward soft and hybrid architectures, driven by user acceptance requirements and the need for devices that conform naturally to the human body. This transition is inherently compatible with the TSA mechanism, whose string-based, compliant force transmission imposes no rigid elements between the actuator and the load. Because TSA actuation is inherently soft by definition, the structural distinction across reviewed devices is not rigid versus soft but rather soft versus hybrid - where hybrid designs retain a rigid frame for joint axis alignment while relying entirely on TSA strings for force transmission. This architectural flexibility positions TSA technology as uniquely suited to the next generation of wearable robotics, in which user comfort and compliance are as critical as force output.

With respect to control, intent-driven strategies based on the fusion of sEMG and IMU signals have emerged as the dominant paradigm for assistive and augmentation devices, enabling proactive, user-synchronized assistance that is temporally aligned with voluntary effort rather than lagging behind it. However, standardized and adaptive control strategies remain an open research problem, particularly for rehabilitation applications where the control law must evolve continuously in response to patient recovery progress through patient-in-the-loop architectures. The TSA non-linear force-displacement relationship mechanism further complicates closed-loop design, motivating

the development of more sophisticated model-based and data-driven compensators across future platforms.

Collectively, the evidence presented in this review positions TSA-based wearables as a mature yet rapidly evolving field. The ongoing convergence of lightweight and durable string materials, miniaturized multi-modal sensing, and bio-inspired adaptive control is steadily advancing TSA technology toward viability as both a clinical rehabilitation tool and an industrial assistive platform. Realizing this potential will require the research community to address the identified gaps in anatomical coverage, most notably the shoulder and ankle, alongside the pressing challenges of long-term mechanical durability, real-world clinical validation, and standardized performance evaluation. As these challenges are met, TSA-based wearable devices are well positioned to transition from laboratory prototypes to mainstream tools for human physical augmentation, assistance, and recovery.

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