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Twisted string actuators: Comprehensive review on modeling, design innovations, application advances, and future challenges ☆

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ABSTRACT

Twisted string actuators (TSAs) have emerged as a promising class of soft actuators with diverse applications in fields such as robotics, biomedical engineering, and wearable technology. This review article provides an overview of recent advancements in TSA technology, discusses the challenges associated with their implementation, and explores potential future directions in research and development. Key topics covered include the working principles and mathematical models of TSAs, design solutions, materials selection, fabrication techniques, control, applications, limitations, and avenues for further innovation. By examining the current state of TSA research, this article aims to stimulate discussion and inspire new avenues of exploration in this exciting field.

Contents

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1. Introduction

Robotic systems are spreading in manifold spectra of potential applications and their evolution and adaptation to new challenges require light, reliable, highly efficient actuators. Mechanical transmission systems involving cable twists to transform a rotative motion into a translational motion have been used in machines and mechanisms for centuries. Applications of this transmission system can be found in some ancient machines, for instance, the pump drill [1,2], a hand-powered device used to produce a rapidly rotating motion to a shaft with an alternate linear motion, that can be used for fire-making or as a drill to make holes in various materials, or the torsion siege engine [3], using torsion motion to launch projectiles.

TSAs operate by transforming the rotary motion of an electric motor into a linear motion by twisting a group of strings [4]. Illustrated in Fig. 1, a typical TSA comprises a set of strings, an electric motor, and a load [5]. The strings are coaxially linked to the electric motor on one side and to the load on the other side. The load coaxial rotation is constrained by a prismatic joint. When the motor shaft rotates, strings are twisted and winded together and this deformation causes a contraction. By controlling the motor rotation angle θ, the corresponding contraction ΔL can be exploited to move the load and then to produce the linear motion. High-Density Polyethylene (HDPE) is the prevalent material for the strings, due to its versatility and durability properties and the high strength-to-weight ratio.

The advantages of TSAs lie in their ability to produce high tensile force with low input torque and their simple mechanical muscle-like structure [6]. TSAs are lightweight, cost-effective, and inherently compliant. With the efficiency factored in conventional DC motors, their efficiency can reach values up to 85% [7], even if this parameter is strongly dependent on the twisting angle, and boast a reasonably high power density of 0.5 W/g [6]. In particular, designers exploit considerable freedom because the motor can be placed coaxially with the axis of motion.

However, TSAs still present several open challenges. Notwithstanding the stroke of a TSA can be mathematically defined as a function of motor rotation angle, its control requires particular attention due to the highly non-linear transmission ratios, decreasing as the string is twisted [8]. Lifetime can be a concern, as repeated twisting and untwisting may cause the strings to be worn or damaged [9]. Furthermore, TSAs exhibit limited bandwidth and contraction ratio [10].

Current research on TSA focuses on different and complementary aspects, that in this work have been divided, for the sake of organization, into modeling, design, control and applications.

Contribution and paper organization. The scope of this work would encompass a comprehensive examination of current state-of-the-art technologies, developments, applications, challenges, and perspectives related to TSA. The rest of the review article is organized as follows: Section 2 illustrates the criteria adopted to identify and classify the reviewed works. The selected papers were split up into four groups, depending on their main contributions, namely (M) modeling, (D) design, (C) control, (A) application. The following sections resemble and deepen the results of this classification: Section 3 summarizes the main functional aspects and mathematical models of TSAs, Section 4 discusses about their design details and specific implementations, Section 5 presents an overview on control methods, Section 6 summarizes the main TSA applications. On the basis of this analysis, Section 7 discusses on current challenges and opportunities of this type of actuators and presents the most promising future development directions. Section 8 wraps up the main paper contents and concludes the work.

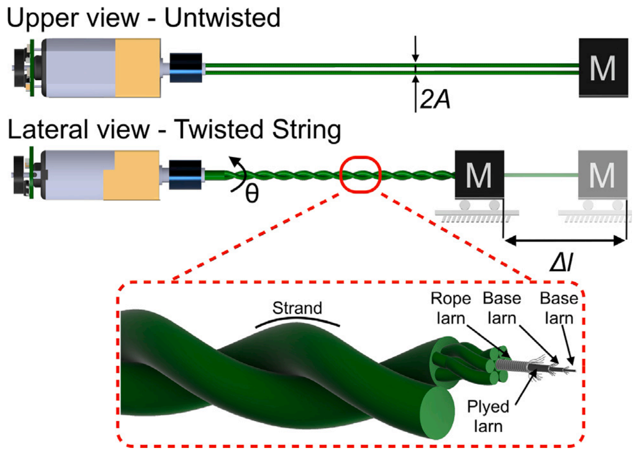
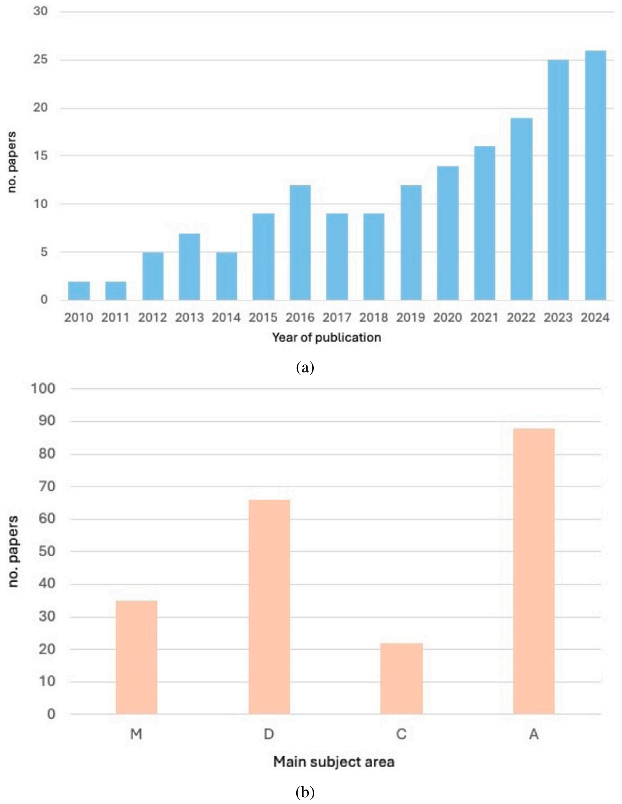


Fig. 1. TSA scheme: the top section provides a top view of the TSA assembly. The bottom section shows a lateral view illustrating how the TSA twists two strings. An enlarged detail view focuses on the twisting phenomenon, specifically highlighting the interactions occurring within each individual string.

2. Materials and methods

We use the Scopus database to implement this review and in the first phase of the analysis, we extracted articles published until April 2025 in international journals and conference proceedings. To provide an overview of TSA development, we used the keywords: *"twisted AND string AND (actuator OR mechanism)"* as search terms. We limited the research to the following *Subject Areas*: *Engineering*, *Computer Science*, *Materials Sciences*. The research provided 202 items, among them, 25 were considered out of the scope of this research (8 of them were *Conference Reviews*, the remaining 17 were out of the topics of this paper), while 177 were further analyzed. It is worth noticing that none of the papers identified with these criteria was a review. A first overview of the selected papers, represented as the number of resources per publication year (from 2010 to 2024), is reported in Fig. 2(a).

The selected papers were further classified according to their main topic into four groups: (M) modeling, (D) design, (C) control and (A) application (Fig. 2(b)). Some papers could not be classified in a single group and therefore were counted more than once in Fig. 2(b). In



(a)

(b)

Fig. 2. Results of Scopus research. (a) Number of resources per year from 2010 to 2024 and (b) per main topic (M = modeling, D = design, C = control, A = application).

particular 32 papers were considered in 2 groups, and one of them [11] in 3.

Twisted String Actuators were introduced in 2010 by Würtz et al. [12], firstly presenting the mechanism and its model, and by Godler and Takashi [13], who proposed an application of TSA to a five fingered robotic hand. TSA applications were initially limited, while their diffusion has significantly increased from 2019. Since their compactness and high force transmission ratio make them particularly effective in robotics applications, they were applied to articulated robotic hands and exoskeletons since their first introduction [14,15], where very strict dimension and weight requirements are needed.

While analyzing the selected papers, the research was integrated with other resources (cited by- or citing the above-mentioned works), to complete the analysis of the different aspects. The results of the review are reported in the following sections.

3. Working principles and models of twisted string actuators

3.1. Considerations on twisted string actuator principles, models, and materials

The typical TSA setup consists mainly of an actuator and two strings attached to the motor shaft. As the motor rotates, the strings wind around at a helical angle, and the twisting effect produces a contraction translating motor rotation into linear motion. The scheme of a typical TSA module is shown in Fig. 1.

The primary component of twisted string actuators is a polymer fiber, chosen for its mechanical properties and suitability for deformation. Nylon, and High-Density Polyethylene (HDPE) are commonly used due to their high strength, flexibility, and availability [16].

The process begins with the polymer fiber twisted along its axis while under tension. This twisting creates a helical structure along the length of the fiber, storing potential energy within its molecular bonds. The degree of twist applied to the fiber determines the magnitude of the resulting contraction when the tension is released [17]. When the applied tension is released partially or completely the stored potential energy is converted into kinetic energy. As a result, the twisted fiber begins to untwist, returning to its original untwisted state. The twisting motion of the polymer fiber causes it to contract along its length. This contraction generates a pulling force, which can be harnessed for various mechanical tasks or movements, depending on the configuration and application of the actuator. The contraction value and the resulting force output of the actuator can be controlled by adjusting system parameters, including the degree of twist applied to the fiber, the tension, and the characteristics of the polymer material itself. Such parameters allow precise tuning of the actuator's performance to meet specific application requirements [18].

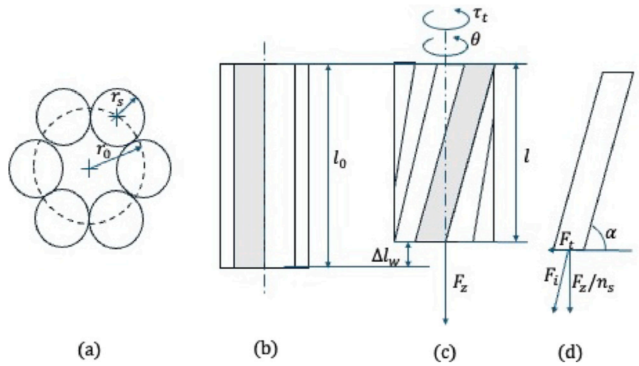


Fig. 3. Scheme of TSA composed of $n_s = 6$ strings, main parameters to define the mathematical model according to [12]. (a) Cross section. (b) Lateral view, reference configuration. (c) Lateral view, twisted configuration. (d) Lateral view, twisted configuration, detail of one string.

TSAs exhibit inherent compliance and flexibility due to the properties of the polymer fiber and the helical structure formed during twisting. This flexibility enables the actuators to bend, deform, and adapt to their surroundings, making them well-suited for applications requiring interactions with complex shapes or delicate objects [19,20].

The forward kinematic relationship between the motor rotation θ and string contraction ΔL is nonlinear, due to the above-mentioned twisting mechanism. Such a relationship has been investigated from the first works on TSA [12,13].

3.2. Introducing the twisted string actuator model

In this subsection, we summarize the first mathematical models of TSA, introduce in the preliminary works on this actuation type presented in 2010. The mathematical symbols adopted in the description of the model are collected in Table 1.

One of the first TSA mathematical models was presented in the paper authored by Würtz et al. [12], and assumes a TSA composed of n_s strings, each with radius r_s. A scheme of the system with $n_s = 6$ is presented in Fig. 3. Let us consider a configuration in which the strings are twisted to form a helix with angle α, let us indicate with r_0 the helix radius, with F_z the tensile force applied to the strings, and with τ_t the torque applied by the motor. Assuming that the motor torque is equally distributed over all the strings, each string is subject to a force F_t on the plane perpendicular to TSA axis given by

$$F_t = \frac{\tau_t}{n_s r_0} \tag{1}$$

Assuming that each string can resist tensile forces only, *i.e.* it can be considered as an ideal cable, the tensile force acting on each string can be expressed as:

$$F_i = \frac{F_t}{\sin\alpha} = \frac{\tau_t}{n_s r_0 \sin\alpha} \tag{2}$$

Table 1
Summary of symbols (in alphabetical order) adopted to describe in the mathematical model.

Symbol	Meaning	Dimension (SI units)
k_s	String tensile stiffness	Force/length (N/m)
l	Distance between the motor shaft and the load in a generic configuration	Length (m)
l_0	Distance between the motor shaft and the load in the reference configuration	Length (N)
l_{0s}	String longitudinal dimension in the reference configuration	Length (m)
l_s	String longitudinal dimension in a generic loaded configuration	Length (m)
n_s	Number of strings	Integer
p	Helix pitch	Length (m)
p_{min}	Minimum possible value of helix pitch	Length (m)
r_s	String radius	Length (m)
r_0	Helix radius	Length (m)
v	Load velocity	Speed (m/s)
A	Distance between string attach point on the load and TSA axis	Length (m)
F_i	Tensile load applied on each string	Force (N)
F_t	Tensile load applied on each string, component on the plane orthogonal to TSA axis	Force (N)
F_z	TSA equivalent load	Force (N)
α	Helix angle	Angle (rad)
α_{min}	Minimum value of helix angle	Angle (rad)
θ	Twisting rotation	Angle (rad)
$\theta_{max,G}$	Maximum value of twisting angle evaluated as in [13]	Angle (rad)
$\theta_{max,W}$	Maximum value of twisting rotation evaluated as in [12]	Angle (rad)
$\rho_{max,G}$	Maximum contraction ratio as in [13]	Non dimensional
$\rho_{max,W}$	Maximum contraction ratio as in [12]	Non dimensional
τ_t	Torque applied by the motor	Torque (Nm)
ω	Motor angular speed	Angular speed (rad/s)
Δl	TSA stroke	Length (m)
Δl_G	TSA stroke evaluated according to [13]	Length (m)
Δl_W	TSA stroke evaluated according to [12]	Length (m)

The force F_z needed to balance the torque τ_t is then given by

$$F_z = n_s F_i \cos\alpha = \frac{\tau_t}{r_0 \tan\alpha} \tag{3}$$

Indicating with k_s the tensional stiffness of each string, normalized with string length, when the strings are twisted and subject to the pulling force F_z, the length of each string is given by

$$l_s = l_0 + \frac{F_i l_0}{k_s} = l_0\left(1 + \frac{F_i}{k_s}\right) \tag{4}$$

Indicating with θ the twisting angle, the TSA twisted length l and the TSA contraction Δl_W can be evaluated as:

$$l = \sqrt{l_s^2 - (r_0\theta)^2}, \quad \Delta l_W = l_0 - l. \tag{5}$$

The helix angle α and the helix pitch p are given by:

$$\alpha = \arcsin\left(\frac{l}{l_s}\right), \quad p = \frac{2l\pi}{\theta}. \tag{6}$$

The minimum value of the pitch depends on the radius and number of the strings and can be defined as

$$p_{min} = 2 n_s r_s, \tag{7}$$

corresponding to the configuration in which the helix coils are in contact with each other. This constraint allows us to define a maximum limit of twisting angle:

$$\theta_{max,W} = \frac{2\pi l(\theta_{max,W})}{p_{min}} \tag{8}$$

By considering the l_s expression in Eq. (4), θ_{max} can be expressed as:

$$\theta_{max,W} = \frac{l_0\left(1 + \frac{F_i}{k_s}\right)}{\sqrt{\frac{n_s^2 r_s^2}{\pi^2} + r_0^2}} \tag{9}$$

The maximum contraction ratio $r_{max,W}$ that can be obtained from the TSA before overtwisting occurs is then given by:

$$\rho_{max,W} = \frac{\Delta l_W(\theta_{max,W})}{l_0} = \frac{l_0 - l(\theta_{max,W})}{l_0} \tag{10}$$

The model has been integrated in [4] with differential kinematics and dynamics relationships and in [16,21] considering string radius variation during twisting.

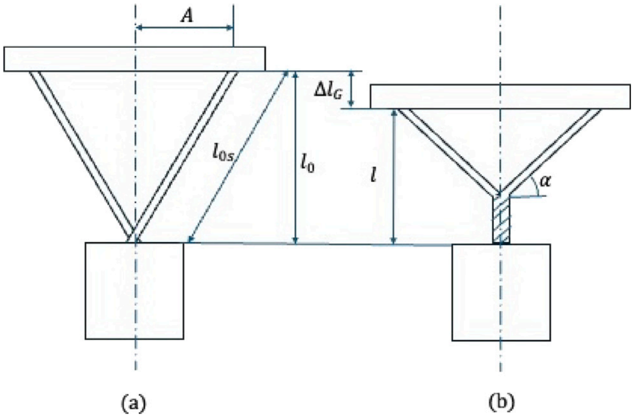


Fig. 4. Scheme of TSA with $n_s = 2$ strings, main parameters to define the mathematical model according to [13]. (a) Lateral view, reference configuration. (b) Lateral view, twisted configuration.

Godler and Sonoda [13] solve the problem with different assumptions, in particular they consider $n_s = 2$ strings that on the side opposite to the motor are attached to the load at a distance $2A$. Based on the scheme in Fig. 4, let us define l as the distance between the motor shaft and the mass indicated with M. When the actuator is unloaded and untwisted, string length is given by $l_{0s} = \sqrt{(l_0^2 + A^2)}$. When the motor rotates, the pair of strings coils into a helix with radius $r_0 = r_s$, resulting in a contraction Δl_G, that correlates with the motor rotation θ as described by the following relationship:

$$\Delta l_G = l_0 - \sqrt{l_{0s}^2 - (A + r_s\theta)^2}. \tag{11}$$

It is worth noticing that under the same hypotheses, *i.e.* inextensible strings and $A = 0$, the kinematic relationships in Eqs. (5) and (11) are coherent. The helix angle α can be calculated as:

$$\alpha = \arcsin\left(\frac{\sqrt{l_{0s}^2 - (A + \theta r_s)^2}}{l_{0s}}\right). \tag{12}$$

The minimum value of the helix angle α_{min} is obtained when the coils are in contact with each other. With two strings, this condition is verified for a helix pitch $p_{min} = 4r_s$, corresponding to an helix angle α_{min}:

$$\alpha_{min} = \arcsin\left(\frac{4r_s}{2\pi r_s}\right) = \arcsin\left(\frac{2}{\pi}\right). \tag{13}$$

It is worth noticing that in the hypothesis that the helix radius $r_0 = r_s$, α_{min} is independent from string radius. The corresponding maximum rotation angle $\theta_{max,G}$ is:

$$\theta_{max,G} = \frac{\pi l_{0s} - A\sqrt{\pi^2+4}}{r_s\sqrt{\pi^2+4}}. \tag{14}$$

The maximum contraction ratio $r_{max,G}$ that can be obtained from the TSA before overtwisting occurs is then given by:

$$\rho_{max,G} = \frac{\Delta l_G(\theta_{max,G})}{l_0} = \frac{l_0 - \sqrt{l_{0s}^2 - (A + r_s\theta)^2}}{l_0}. \tag{15}$$

It is worth noticing that, assuming $r_0 = r_s$, $n_s = 2$, $A = 0$, $F_z = 0$, the models are equivalent and it results [4]:

$$\theta_{max,W} = \theta_{max,G} = \frac{\pi l_{0s}}{r_s\sqrt{\pi^2+4}}, \tag{16}$$

and

$$\rho_{max,W} = \rho_{max,G} = 1 - \frac{2}{\sqrt{4+\pi^2}} \approx 46\%. \tag{17}$$

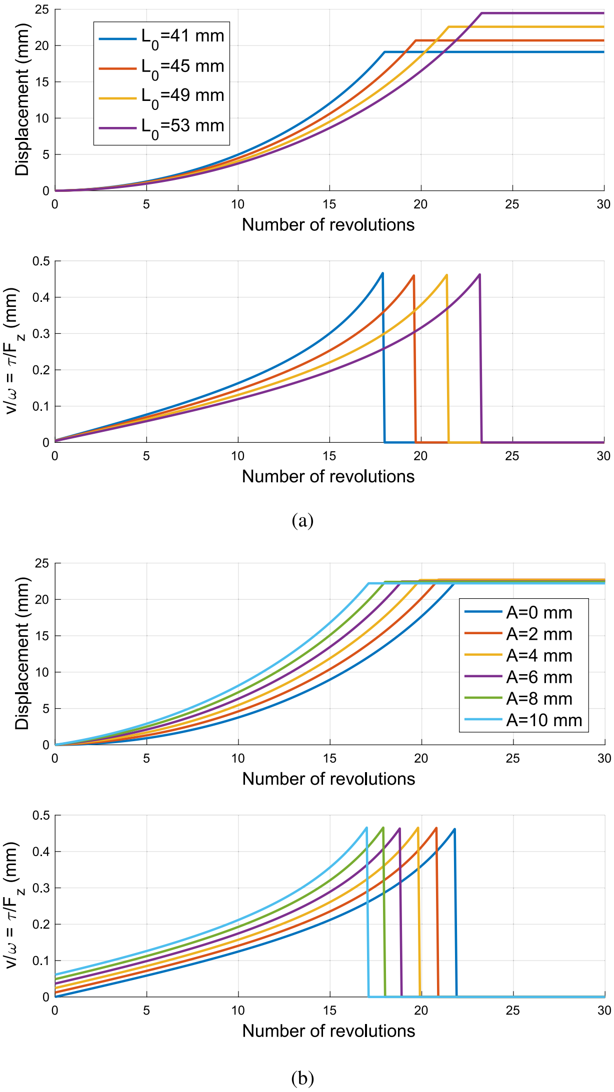
Beyond the values $\theta_{max,W}$ and $\theta_{max,G}$, the previously introduced models are unable to define reliable kinematic relationships and overtwisting phenomena are observed, characterized by high hysteresis and significant non-linearity [4].

The kinematic relationship in Eq. (11) can be differentiated to define the TSA transmission ratio between TSA translation velocity v and actuator rotation speed ω:

$$\frac{v}{\omega} = \frac{r_s(A + r_s\theta)}{\sqrt{l_{0s}^2 - (A + r_s\theta)^2}}. \tag{18}$$

Exploiting the Principle of Virtual Work, assuming 100% mechanical efficiency, the right-hand term in Eq. (18) also expresses the ratio between the motor torque τ_t and pulling force F_z in quasistatic conditions. In [5] the model has been integrated and its results have been compared with experimental tests on a TSA prototype

A numerical evaluation of the TSA kinematics with parameters r_s = 0.30 mm, A = 0.75 mm and l_{0s} varying between 41 and 53 mm is reported in Fig. 5(a), while Fig. 5(b) reports the results obtained with l_{0s} = 49 mm and A varying from 0 to 10 mm. The behavior is non-linear until the θ_{max} value is reached. For higher values of θ angles the displacement is conventionally set constant.



(a)

(b)

Fig. 5. Numerical evaluation of the TSA kinematics (displacement vs. number of motor revolutions) according to the model presented in [13]. (a) TSA displacement ΔL_G vs. number of motor revolutions for different values of L_0. (b) TSA displacement ΔL_G vs. number of motor revolutions for different values of A distance.

3.3. Model developments

The models introduced in the previous section have been further studied and detailed, introducing additional parameters and physical phenomena to improve their capability to represent TSA dynamic behavior.

In [17], the mathematical model has been further developed by introducing friction between strings during twisting, while in [22] the contact of TSA with a guide is considered. In [23] the authors focus on model development to take into account string tension and friction, to improve the accuracy in control systems. In [24] the model of a bi-directional TSA system is proposed, focusing in particular on the role of the number of strings in system main performance.

Besides the kinematics and statics problems, reliable system dynamics models are needed to predict and assess system behavior when periodically repetitive trajectories are required and system natural frequencies could influence system performance. The model presented in the previous section has been integrated in [18] with the evaluation of mechanical energy and dynamics equations. Their work introduces an extended dynamical model that accounts for the elastic deformation of strings and frictional forces, enabling more accurate estimation of required motor torque across a wide range of motion frequencies, corresponding to bandwidth up to 2 Hz. Experimental validation of this model showcased a relative error between theoretical and practical curves of no more than 7%, a level of accuracy previously unattainable with existing mathematical models.

In [25] the TSA analytical model is further detailed, based on the observation that the twisting process can be non-homogeneous in axial direction, due to the friction between the strings.

TSA models are needed to predict system dynamic behavior, but are also useful to define quantitative metrics for system evaluation and assessment. In [26] the authors propose to evaluate TSA's performance in terms of (1) contraction range, (2) linear velocity, (3) torque input, (4) force output, (5) effect of string bundle radius, (6) effect of string offset.

The TSA model has been elaborated in [27] to present it as a synthesis tool, to choose the main design parameters of a TSA system based on the design requirements.

More recently, Bombara et al. [11] introduced TSA based on compliant strings, composed of thermally-activated, and conductive supercoiled polymer (SCP), which can produce large strain, and are capable of self-sensing. In the paper, the compliant behavior is detailed. The behavior of a TSA where strings pass through a conduct is analyzed, both from the modeling and experimental point of view, in [28]. The problem of sets of twisted strings under different pulling forces is studied in [29] by employing the Cosserat rod theory, in particular the connections between geometrical transformation and mechanics are clarified by considering geometric nonlinearities and self-contact.

One of the main limits of TSA is represented by their finite contraction percentage, usually constrained by overtwist limits as previously described in Section 3.2. For example, in the study presented in [26] the authors obtained a maximum contraction ratio of 30%, contraction ratios up to 25% were employed in the systems presented in [30,31]. In [32] the authors experimentally observed the overtwisting in their TSA-based system for contraction ratios varying from 9% to 19%, with a number of strings n_s varying from 2 to 8. In that work, the authors actively exploited the overtwisting phase to increase the contraction percentage up to 81%. The paper introduces this feature also from the modeling point of view.

3.4. Models for sensing and parameter identification

The availability of TSA mathematical model is useful to estimate system status on the basis of measures obtained from sensors. In [33] the authors present a method for TSA force estimation based on a load cell positioned on a pin separating the strings, force estimation is performed with model-based correlations. The sensing capabilities of TSA have been further investigated with experimental tests and analytical models in [34]. In [35] the authors investigated on the possibility of providing sensing capabilities to TSA tendons through the insertion of conductive yarn. The work includes a model analysis for the characterization of TSA deformation and tendon electrical conductivity properties. Self-sensing properties of TSA are investigated also in [36] with experimental tests.

System parameter identification is another problem that in TSAs is particularly challenging, due to the nonlinear behavior. In [37] the authors present a nonlinear identification procedure employing the Nelder Mead simplex method. In [38] the authors propose a method to estimate the output TSA state based on payload's acceleration measurement through an IMU (Inertia Measurement Unit) sensor. In [39] a parameter estimation method assuming little or no knowledge about the system parameters is presented, employing the least squares algorithm and gradient algorithm.

3.5. Data-driven models

As previously introduced, TSA models are based on several parameters and often simplifying assumptions are needed to analytically solve the kinematics direct and inverse relationships. Furthermore, the system is nonlinear and presents phenomena that are difficult to model or quantify, for example friction, hysteresis, plastic deformations, etc. Data-driven models represent an alternative method for defining system properties. Examples of this type of model, based on Artificial Neural Networks, is presented in [40,41]. A neural network-based inverse model of TSA dynamics is realized in [42] to reduce model errors and handle nonlinearities between the inputs and outputs.

3.6. Model applications

TSA models can be integrated with the models of the wider system that they are actuating. For example, in [43] the TSA model is integrated in a soft robotic model, in particular an inverse kinematic model is developed to realize an open-loop control for a soft robotic manipulator. The kinematic model of a soft actuator for robotic applications based on TSA is presented in [44], while the integration of TSA model in an anthropomorphic robotic gripper is presented in [45]. A recent and interesting application is presented in [46], where the authors exploit individual string contraction to obtain a differential mechanism.

4. TSA design configurations

The TSA principle has been exploited in different design solutions. This section discusses TSA design, implementation, technology, and prototyping aspects and summarizes the main solutions identified in the literature research.

4.1. Unidirectional vs. bi-directional actuation

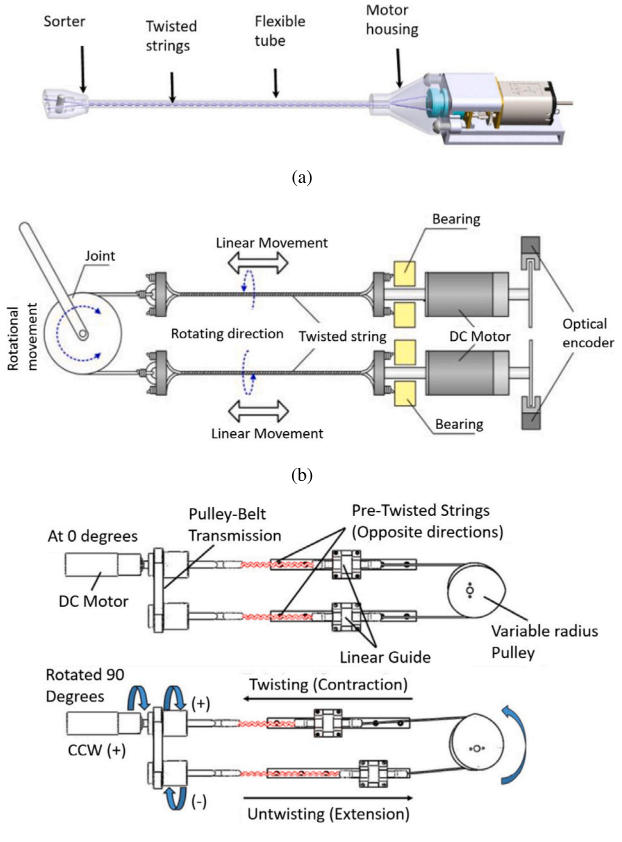
TSAs work as a rotational to linear transmission system based on flexible elements and therefore can transmit the motion in one direction only. Similarly to any other cable-driven transmission systems, TSA can be arranged in antagonistic configuration to provide a bi-directional actuation. In antagonistic actuation, TSAs are arranged in pairs, with each pair consisting of two TSAs working in opposite directions. In this setup, one TSA contracts while the other extends, creating opposing forces. This antagonistic arrangement enables controlled and precise movements, similar to the action of human muscles in pairs (agonist and antagonist muscles) that work in opposition to produce coordinated motion.

Each configuration has specific characteristics, advantages, and limitations and its employment depends on the specific operational requirements. From this point of view, the current state of the art presents three main configurations.

Unidirectional TSA actuation system. This setup (Fig. 6(a)) involves a single TSA that generates motion in one direction (pulling) when activated. This configuration is usually employed when an active control of motion is required in only one direction, and passive return elements (e.g. springs) can be adopted since limited force in the reverse direction is required, for example in grippers [47]. To achieve both large force/torque output and compactness in a TSA, Lee et al. [48] and Souza et al. [49] present solutions where groups of parallel strings are assembled in a bundle, actuated by a single motor and a gear system.

Bi-directional (antagonistic) TSA actuation system using two motors. In this solution (Fig. 6(b)), two TSAs are arranged in antagonistic configuration, i.e. they work in opposition to each other. Each actuator is driven by a separate motor, allowing for bi-directional motion control. This setup is often used in robotic joints or limbs where precise control over both extension and contraction is necessary, as presented for example by Jiang et al. [50].

Bi-directional (antagonistic) TSA actuation system using a single motor. Similar to the previous setup (Fig. 6(c)), this configuration employs two TSAs arranged antagonistically. However, in this case, both the TSAs are driven by a single motor through a mechanism, usually gear-based, that enables bidirectional movement. This setup offers a more compact and integrated solution compared the previous one, as discussed by Lee et al. [51].



(a)

(b)

(c)

Fig. 6. Various configurations of straight TSA actuation system. (a) Unidirectional TSA actuation system [47] where is shown a single-motor TSA assembly with the sorter and the flexible tube that houses the strings within the twisting zone. The sorter pin acts as an interruption mechanism to stop the twisting effect and confine it to the designated twisting area. (b) Bi-directional (antagonistic) TSA actuation system using two motors [50]. (c) Bi-directional (antagonistic) TSA actuation system using single motor [51].

4.2. Non-linear pulley

Since the nonlinear behavior of TSA could impact system performance and the definition of efficient control, different solutions for obtaining a linear transmission system through TSA have been presented in the literature. Mehmood et al. [52] designed a yoke mechanism for linearizing the kinematic relationships in a TSA for actuating a wearable exoskeleton for elbow application, and in particular for obtaining a linear relationship between TSA motor rotation and elbow joint angle. Jeong et al. [53] developed a compact clutch system mechanism that allows for achieving a simplified two-stage transmission ratio by adjusting the radius of the twisted string. Another solution presented by the same research group [54] implements an active gear-based dual mode system for string actuation. In [55] a variable radius pulley is designed to linearize the TSA input–output. Furthermore, a bidirectional transmission systems driven by a single motor is proposed.

Another interesting implementation exploiting the nonlinear behavior of TSA was developed by Kim et al. [56], which propose a combination between TSA and continuously variable transmissions based on elastomeric materials to obtain a behavior mimicking muscles. In particular, they propose an Elastomeric Continuously Variable Transmission (ElaCVT), which extends TSA operational capabilities. By mimicking the force-velocity curve of muscles through passive alteration of the reduction ratio in response to external loads on the TSA's end, ElaCVT enhances the adaptability and performance of linear actuators. The integration of ElaCVT with TSA, referred to as ElaCVT-TSA, represents a significant stride toward developing actuators that replicate muscle characteristics. Unlike conventional mechanisms, ElaCVT achieves reduction ratio adjustments through elastomer deformation, simplifying design complexities. This compact and lightweight CVT design facilitates its integration into diverse robotic systems.

The Adaptive variable-radius pulley presented by Park et al. [57,58] is an efficient idea for Antagonistic TSAs. Unlike conventional transmission systems, which are cumbersome and require additional actuators, this pulley system is simple, lightweight, and capable of passively adjusting its transmission ratio based on the output load. The versatility of the variable-radius pulley enables its seamless integration into existing tendon-based robot platforms without the need for extensive modifications. By dynamically altering the pulley's radius, the transmission effect can be directly applied to enhance the system's performance where the TSA is employed, e.g. robotic platforms, exoskeletons, etc.

4.3. Contact with sliding surfaces

One of the issues related to TSA implementation is that the twisting string should not be in contact with any obstacle or external surface, because this contact would modify the twisting propagation along the string, varying the transmission properties and, eventually hindering the string twisting. To avoid this problem, Palli et al. [22,59] analyzed the behavior of a TSA inserted in a sheath and, more generally, investigated the contact between the twisting string and a sliding surface. Suthar et al. [7] propose to insert the TSAs inside a conduit, and verify that the string twist can propagate through the sheath and that consistent periodic behavior of the twisted string can be achieved. Both these studies presented an experimental investigation on the behavior of a twisted string within a conduit at various constant deflection angles, alongside an examination of the impact of lubrication on cable hysteresis within conduits. Results indicate that twisting the cable achieves consistent behavior in terms of position and tension forces, with higher transmission efficiency and lower friction compared to sliding. Lubrication further improves force transmission efficiency. However, during untwisting, chattering behavior occurs due to resistance from remaining twists, potentially solvable by pre-twisting the string.

4.4. Lifecycle, fatigue effects

A thorough understanding of the relationship between a twisted string's lifespan, material properties, and operational conditions is still an open challenge in TSA development. Usman et al. [9] presented initial findings from a comprehensive experimental analysis of TSA performance, examining different string materials and operating environments. The study investigated in particular the lifespan of two distinct strings, proposing an empirically derived mathematical model that correlates TSA operational parameters and string characteristics with their endurance. Key observations reveal an exponential decrease in string lifespan with increased load forces and stroke, while the number of strings shows a linear, albeit non-direct, relationship with lifespan.

4.5. Other design developments

The flexibility and adaptability of TSA open several opportunities in the design of compact and versatile mechanical transmission systems.

To overcome the inherent limitation of TSAs represented by their uni-directional action, in [60] a passive extension mechanisms based on buckling effect is presented. The proposed solution is simple and compact and provide a nearly-constant extension force throughout the operation range.

In [61] the authors integrate multiple TSAs in an elastic tube. Specifically, 3 TSAs are arranged in series and 6 in parallel, so that the resulting array can bend in three dimensions with a muscle-like behavior and elastic properties.

In [62] a system for enhancing the maximum stroke of TSA by adjusting twisting ratio with a planetary gear is presented. A TSA mechanism with an adjustable offset between strings, enabling a variable transmission ratio, is presented in [63]. The design of a compact and lightweight TSA module suitable for wearable robotic and haptic devices is presented in [64], characterized by an integrated force sensor based on optoelectronic components and an embedded controller with power electronics. Xu et al. [65] developed a TSA system with a continuously variable transmission utilizing lightweight hyperelastic slender rods: by manipulating the distance between two twisted strings through rod deformation, the transmission ratio continuously adapts to varying load conditions.

A compact transmission module based on TSA is presented in [66], which implements an input–output transmission shifting mechanism by changing the twisted radius. Jeong et al. [54,67,68] propose a dual-mode TSA system, where a two-stage transmission ratio is implemented. The transmission is designed to switch the twisted radius of the string between two stages, named force mode or speed mode.

Inspired by TSA structure, in [49] the authors propose an actuation system based on a rotary helix structure that can generate a large contraction force with a small input torque. The helix structure in this case is realized with structural elastic elements (compression springs).

5. Control systems for twisted string actuators

The nonlinear characteristics of TSAs need particular attention in the design of control systems. In this section, we summarize the main research activities and the main results in TSA control. The analyzed resources are listed in Table 2 and briefly described in the following. For the sake of organization, the references were grouped on the basis of the type of proposed control system.

5.1. Position control

Position control algorithms set a reference position, that need to be followed by the actuation system. Position control system can operate in the actuator space, when a reference value for the motor rotation θ_{des} is set, or in the end-effector workspace, where the desired TSA stroke ΔL_{des} is set. Urukalo et al. [8] introduced a comprehensive work including modeling, design, and control work of a TSA. Lee et al. [69] evaluate both proportional–integral–derivative (PID) control and time delay control (TDC) in the TSA position control. In [70] the authors present and compare the performance of two PID-based and LQR-based position controllers. In [71] the authors develop a PD position control compensating system nonlinearities and tracking errors. A position control system for the dual-mode TSA introduced in [54] is presented in [72].

A dual-direction actuating mechanism is needed to precisely control the displacement of TSAs in both extension and contraction directions. Jiang et al. [50,70] propose two controllers considering the cross-coupling dynamics between the two directions. In [73] the authors present a position control system for a robotic system where a pair of antagonistic TSAs are implemented.

Based on the identification procedure mentioned in Section 3.4, in [39] and adaptive position control algorithm is presented and tested through numerical simulations.

In [74] the authors present a high-precision control for TSA achieved by implementing a modal-space disturbance observer, designed to realize an acceleration-based control. Furthermore, the workspace observer can estimate the force applied force.

In [75] the authors present optimal an algorithm for point-to-point transitions with TSA, introducing in particular a method to generate smooth trajectories by directly solving an optimal control problem that considers constraints on motor torque and speed and preventing loss of tension in cables. In [76] the authors present an adaptive control methodology that increases the bandwidth of TSA-based systems, based on an accurate model that considers nonlinearities of the system.

5.2. Force control

Most of the studies available in the literature are focused on position control, while fewer focus on force or impedance control. One solution for force control exploits the use of external force sensors connected to the robotic structure to be controlled, as for instance in the robotic hand presented in [77]. Baek and Ryu [78] propose an indirect tension control method for TSAs, while the system proposed by Hossein [79] includes a force sensor for measuring and controlling string tension in a wearable exoskeleton.

Most of the presented control systems manage nonlinearities through a model-driven approach or employing control strategies compensating them, other possible solutions leverage on data-driven approaches, for example in [42] a learning-based force controller is designed using the input and output data of TSAs without a dynamic model. The trained neural network-based inverse model is directly implemented as a force controller.

5.3. Impedance control

Impedance control systems are implemented when both end effector trajectory and variable stiffness need to be controlled, for example when the system interacts with environmental dynamics and neither force control nor position control are sufficient on their own to manage a safe and reliable interaction with the environment in realistic settings. An impedance control of TSA implemented on tensegrity robots is presented in [80]. An adaptive impedance control for a TSA actuated wearable lower limb exoskeleton for emiparetic patients is proposed in [81], where the robotic actuation is evaluated on the basis of both motion and physiological reference of the healthy limb and the performance of the impaired limb. The problem is formulated as a linear quadratic regulation to minimize the bilateral trajectory tracking errors and human effort. A reinforcement learning algorithm is designed to solve the given optimization problem to evaluate the impedance parameters.

5.4. Hybrid control

Rodriguez et al. [82] propose a hybrid control scheme based on two nested loops, considering the motor angle and the axial force at the clamping point of the actuator as the system outputs. They use the axial force measure at the base of the actuator, to estimate and compensate the coupling torque between the motor and the external load, and then formulate a linear control law to control the angular position of the actuator. An MPC (Model Prediction Control) based system for controlling both TSA displacement and tension is presented in [83].

6. Applications of twisted string actuators

As highlighted in the previous sections, TSAs are compact and versatile actuation systems. TSA applications can vary depending on their actuation mode: unidirectional or antagonistic. In this section, the main applications of TSA in different robotic fields found in the above described literature review are briefly summarized.

Table 2
Summary of the main studies on TSA control systems. For each bibliographic reference, the exploited control system is reported.

Reference	Position	Force	Impedance
[8]	x		
[39]	x		
[42]		x	
[70]	x		
[71]	x		
[72]	x		
[73]	x		
[74]	x		
[76]	x		
[78]		x	
[80]			x
[81]			x
[82]	x		x
[83]	x	x	

6.1. *Robotic arms*

TSAs represent an interesting actuation opportunity when the robotic component has to comply with strict requirements in terms of weight and compactness, for instance, a foldable TSA-based robotic arm for drones has been presented by Suthar et al.in [84]. Soft robotic arms and manipulators represent an important application field where the TSA flexibility can be efficiently employed, for instance, Bombara, Konda et al. [43,44] investigated the physical model of a soft robotic manipulator actuated by TSA. Cho et al. [85] present a TSA-based hyper redundant manipulator and propose a tension maintenance system employing compression springs at the distal end of the manipulator to prevent tension losses and to improve controllability properties.

6.2. *Medical and surgical robotics*

TSAs have been exploited in medical and surgical applications and in particular in applications requiring flexibility and small dimensions. Yan et al. [86] presents a TSA-based actuated and controllable catheter for catheter-based interventional diagnosis and therapy. Nica et al. [87] propose a magnetic transmission system based on twisted string to be applied in miniaturized surgical robots. Schlesinger et al. [88] present a TSA-based device with position feedback for robotic endoscopy. For the same application, in [89] a pair of TSAs working in antagonistic configurations are employed. In [90] a video laryngoscope with an adjustable shape is designed, in which the configuration can be adapted to patient's specific needs with a TSA. In [91] an active TSA-based exoskeleton for assisting a surgeon during operations is presented.

6.3. *Robotic hands*

Soft materials and flexible actuation systems are often exploited in the development of robotic hands and grippers to provide them the required adaptability and versatility properties [92]. Due to their compact and flexible structure and to the high force/torque ratio, TSAs are particularly suitable for actuating articulated and soft robotic hands, grippers, and fingers, especially when highly dexterous, anthropomorphic structures are employed. TSAs have been employed in robotic hands and fingers from their first development stages, for example by Sonoda et al. [77,93], Shin et al. [14], Godler et al. [13,30]. Applications of TSA in anthropomorphic robotic hands are presented by Jeong et al. [94], Tsabedze et al. [47], Tavakoli et al. [95], Jin et al. [96], and by Xu et al. [97]. In the European project DEXMART, an anthropomorphic robotic hand has been developed, robotic a lightweight and compact hand mechanism has been realized through the introduction of interesting design solutions, including the use of the twisted string principle [98–100]. In [101] another anthropomorphic robotic hand is presented, actuated by 6 TSAs (2 for the thumb, and one for each finger), fitted within a the palm.

The flexible structure of TSAs can be exploited in the emerging field of soft hands and fingers, as presented for example by Rahman et al. [101]. Tsabedze et al. [102] developed an actuated glove based on TSA that can actuate both robotic and human hands. Godler et al. [30] developed a compliant robotic gripper employing TSA and evaluated its performance. Konda et al. [19] presented a compliant gripper actuated by TSAs, where two actuators per finger are employed: one for finger bending and one for joint stiffening, a similar principle is exploited also in the wave-joints presented by Dragusanu et al. [103,104]. Lee et al. [20] exploited the twisting principle applied to an origami structure to develop a compliant and adaptable robotic gripper. In [105] the authors present the design of a planar robotic gripper that, when driven by a twisted string actuator, exhibits nearly-constant transmission ratio throughout its motion range. In [106] the authors introduce an anthropomorphic soft robotic gripper driven by TSA, named STAR–2. The proposed system has a monolithic structure with a 3-DOF thumb and four fingers, each with 2-DOFs.

6.4. *Prostheses and supernumerary robotic limbs*

TSAs are suitable to realize a convenient transmission ratio from motor torque to tendon contraction force while keeping the structure light, flexible, and compact. This feature is interesting in the implementation of anthropomorphic prosthetic hands such as the one proposed in [96], characterized by six active and 15 passive DOFs, with a weight of 280 g. Another lightweight (390 g) and versatile prosthetic hand actuated by TSA is presented in [107]. A preliminary study on a low-cost active hand prosthesis, based on a TSA differential mechanism, is presented in [108].

Human augmentation via supernumerary robotic limbs is an emerging research field in robotics [109]. Among the possible applications, it is worth mentioning that these devices are becoming an effective method for assisting post-stroke patients in their daily life activities. For example, supernumerary fingers are devices worn on a patient's forearm, providing basic grasping and manipulation capabilities. To meet the lightweight and flexibility requirements of these devices, TSAs represent a possible solution for their actuation, as presented in [110]. Similarly, TSA-based supernumerary arms can support post-stroke patients in bimanual tasks, as presented in [111].

6.5. *Exoskeletons*

The compactness and flexibility of TSAs allow for complying with some of the most demanding requirements in the design of wearable devices for rehabilitation and assistive applications. TSA structure make them suitable for realizing flexible and compact components acting as artificial muscles that can be employed in wearable assistive devices, as shown in [112].

Concerning the lower limbs, Seong et al. [113] adopted TSAs in a hip exoskeleton to reduce the effort in lifting tasks. TSA application for knee exoskeletons have been presented by Zhao et al. [114], Muehlbauer et al. [115], Müller et al. [116], and Huang et al. [117]. A TSA wearable lower limb exoskeleton for emiparetic patients is presented in the above cited [81]. A feasibility study on an ankle-foot active orthosis employing TSA is presented in [118]. In [119] the kinetostatic model of a lever-based lower limb exoskeleton actuated by TSA is presented.

The small dimensions of TSA motors and the string flexibility allow wearable and light exosuits for back support in heavy tasks or treating specific problems. Ali et al. [120–122] propose an active soft brace that allows mobility to the spine while applying controlled corrective forces for scoliosis treatment. Yoon et al. [123] introduce a wearable exosuit that can be stiffened for posture assistance or kept flexible for unrestricted movements as required by tasks. A multi-DOF wearable robot adjustable with TSA is presented in [124] to support the user in lifting and carrying heavy loads. An assistive robot with an active system with TSAs and a passive flat-back alleviation mechanism is presented in [125], the system is designed to conform to the natural human spine curvature and assist the patient in daily activities. In [126] a soft power suit actuated with two TSAs is presented, aimed at reducing physical load on the lower back during lifting operations and static forward bending. The design of the actuated suit is designed to mimic the human body force transmission and to amplify the force generated by muscles and tendons. In [127,128] the authors present a reinforced learning-based control for an exosuit actuated with TSA. In particular, they analyze the human-exosuit coupled dynamic model and propose an adaptive impedance controller for mirror training of hemiplegic patients.

Regarding the upper limbs, TSAs represent an interesting solution for realizing light and wearable structures for support and rehabilitation applications, as introduced by Lee et al.in [129]. In [130] a surface electromyography (sEMG)-driven soft exosuit is presented. The device weighs 1.65 kg only and uses TSAs to perform both single and dual-arm elbow assistive tasks. A bidirectional elbow exoskeleton device based on rotational twisted string actuators is proposed in [31]. Other applications of TSA in exoskeletons for elbow support and actuation can be found in [7,131–134].

Concerning wrist actuation, two different devices, both actuating wrist 3-DOF motion, have been recently presented in [135,136]. The first one employes 6 TSA, the second one 5, in both of them the tracking system is realized with a pair of IMU sensors. A 3-DOF wrist orthosis actuated with 3 TSAs is presented in [137].

The development of active exoskeletons and actuated gloves for the hand is particularly challenging due to the complexity of its biomechanical structure and the richness of movements and tasks required for this important part of the body. Wearable devices for hand rehabilitation have been recently classified by Achilli et al. [138] in three main groups: rigid, soft, and hybrid.

Within this context, soft exoskeletons have gained increasing attention thanks to their ability to easy adapt to the natural movement of the hand minimizing the mechanical constrains. Among the various actuation technologies present in the literature, TSAs are particularly effective in hand actuation for assistive and rehabilitative application. Their inherent compliance, compactness, and high force-to-weight ratio make them well-suited for wearable devices, as demonstrated in previously cited studies [46,47,79,102].

In addition to these works, different research have explored the application of TSA-based mechanism in soft robotic hand exoskeleton. These studies address a wide range of goals, such as the motor function recovery in clinal setting, the daily assistance for people with reduced hand mobility and the integration with virtual reality environments to enhance user engagement and therapeutic outcomes. Li et al.in [139], present a lightweight glove that combines TSA-based actuation with whole-hand motion tracking for immersive VR-based rehabilitation, while Silva et al. [140] propose a biomimetic, tendon-driven soft exoskeleton that leverages myoelectric control for upper-limb recovery. Other developments include a modular glove architecture with the integration of TSA-based flexible enabling the flexion/extension and abduction/adduction movements across all fingers [141,142], and orthotic systems aimed at facilitating daily activities. Muehlbauer et al. [143] introduced an active modular hand orthosis utilizing TSAs, with a focus on modularity and adaptability. The presented device design allows for targeted actuation of individual fingers, offering a scalable approach that can be customized for different levels of motor impairment. Popov et al. [144] developed a portable exoskeleton glove featuring a soft structure and TSA-based actuation, aimed at assisting users in activities of daily living (ADLs) while Hosseini et al. [145] explored haptic feedback capabilities with the Exoten-Glove, which allows users to perceive virtual spring stiffness through tactile interaction. With this work, the authors demonstrate that variations in string tension can be translated into haptic cues, enabling rich user interaction. Tsabedze et al. [146] presented AWARD, an active wearable assistive and resistive device that can support rehabilitation protocols in terms of passive assistance and active resistance for strength training. Still, Tran et al. [147] proposed the FlexoTendon glove, a voice-controlled exotendon system for hand rehabilitation. This glove integrates TSA actuation with natural language control, enhancing accessibility for users with limited motor function.

6.6. *Haptic devices*

Haptic interfaces are becoming common in different applications. The development of effective haptic devices represents another potentially important TSA application field. Skvortsova et al. [148] developed a TSA-based haptic system for controlled actuation of wrist flexion/extension, rendering torque feedback to the joint through a rotary handle driven by a TSA and a spring-loaded cable mechanism. A cable-driven, TSA-based desktop haptic interface has been proposed by Pepe et al. [149]. Van et al. [150] propose a TSA-based system for rendering different tissue stiffness in indenting an anatomical model in medical training. Interesting solutions exploiting TSAs have been recently proposed in the emerging field of wearable haptics. The glove proposed by Hosseini et al. [79,151] can provide users with force feedback while performing virtual object grasping. Leonardis et al. [152] proposed a wearable thimble for rendering the cutaneous perception of contact with a surface. In [153] haptic device with parallel structure, based on TSAs is designed for delivering de-localized tactile feedback in prosthetics. A haptic device with parallel structure combining a TSA with a mechanism for kinematic linearization is introduced in [154].

6.7. *Other applications*

The compactness, flexibility and adaptability properties of TSA make them suitable for many other applications.

Soft robotics represents an emerging research field that focuses on creating robots from flexible, deformable materials that more closely mimic the movements and adaptability of living organisms. Unlike traditional rigid robots, soft robots can bend, stretch, and conform to complex environments, making them ideal for delicate tasks such as medical procedures, exploration in uncertain terrains, and interactions with humans. By integrating materials science, biology, and engineering, soft robotics opens new possibilities for safer, more versatile robotic systems. The inherently compliant TSA structure make this solution particularly suitable for actuating soft robotic structures [155].

Tensegrity robots, for example, are structures composed of continuous tension and discontinuous compression elements, with no rigid joints between elements, which give them peculiar force distribution properties, capable of locomotion and manipulation by changing lengths of their continuous network of tensional elements. The application of TSA in this type of structure is described in [80].

The adaptability and versatility of the TSA can be exploited in robotic locomotion. In [156] TSAs are employed to actuate a 2-DOF joint for snake robots. Another TSA based snake robot is presented in [157]. In [158] TSAs are employed in a wheeled jumping robot.

Origami structures are an interesting solution that can be used in many applications, for example, morphing structures, robotics, and metamaterials. In [159], the authors present automatic procedures for the design of origami structures and, in particular, propose the use of TSA to fold the target 3D structures from flat plates.

Soft-growing robots are soft robotic structures that allow the feeding of new materials at their tips. They have been the object of recent studies because of their peculiar locomotion capabilities. To increase their capabilities in passing through narrow curved passages, Lee et al. [160] present a tip steering mechanism composed of a hyper-redundant rolling contact joint and TSAs.

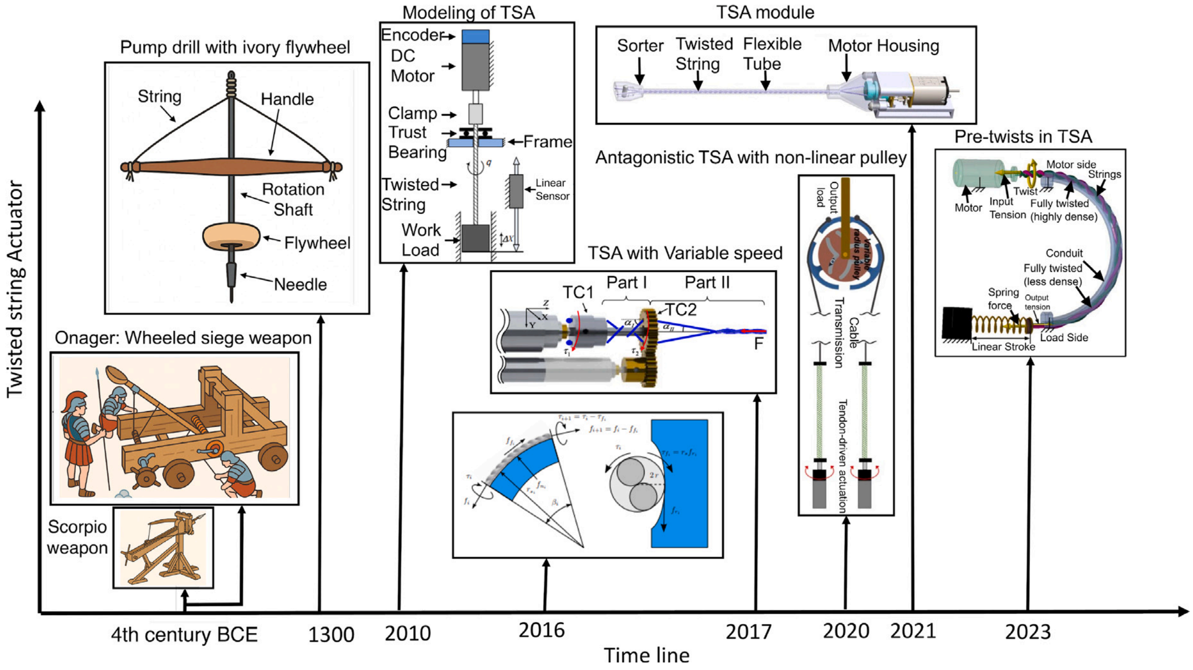


Fig. 7. A graphical description of Twisted String Actuation (TSA) evolution. Pump drills and the torsion siege engine are examples of ancient applications of string twisting-based mechanisms. In the lower left corner, a schematic illustration shows two Roman torsion weapons: the onager (a single-arm torsion catapult) and the scorpio (a torsion-powered ballista). Early torsion artillery emerged during the 4th century BCE, likely during the reign of Dionysius I of Syracuse (399–385 BCE) [166]. The first TSA concepts and models were presented in 2010–2012 [5,12,13,15]. More recently, it is worth mentioning the studies of friction properties of TSA inserted in a sheath presented by Palli et al.in 2016, the dual-stage TSA presented by Jeong et al. [54], the antagonistic configuration with nonlinear pulley presented by Park et al. [57], the studies on TSA inserted in flexible tubes and TSA pre-twist presented by Suthar et al. [28,84]. TSA technology History of TSA development.

An interesting, still preliminary application of TSAs is presented in [161] for aerial manipulation: the system is a net-based design using TSAs to pull together 8 3D printed cylinders connected to a net, which conforms around the object.

In [162,163], the authors propose an actuation mechanism based on TSA to trigger the snap-through of a bistable buckled beam, realizing an on/off bistable actuator. Bistable structures represent an interesting design solution in various engineering applications that only need two simple operating states (e.g. open/close). A bistable structure has two distinct stable configurations, which are suitably robust against disturbances, and they are sustained with no additional external power supply.

7. Results, perspectives and challenges

7.1. Results

Notwithstanding machines including transmission systems based on cable twist to transform a rotative motion into a translational motion have been exploited since ancient times, their systematic study and employment in mechatronic systems is more recent. Fig. 7 graphically illustrates TSA evolution.

The first applications mechanical transmission systems based on cable twisting in robotic and automation systems were proposed by Suzuki et al. [164,165] and are referred to as Strand Muscle Actuators. This simple, yet effective transmission system has been introduced more recently in the so-called Twisted String Actuators (TSAs). In the robotic context, TSAs were introduced in 2010–2012 [5,12,13,15] and their implementation in different robotic applications has been rapidly spreading since 2018–2019 as graphically illustrated in Fig. 2(a).

Overview on TSA modeling. TSA model can be developed by examining the cross-section of the string during the twisting process [4]. As the string undergoes twisting, the degree of contraction can be determined by analyzing the unwound geometry of the cylinder. Through differentiation of this contraction, the relationship between the load velocity and the motor angular velocity can be established. Thus, by specifying the desired contraction velocity, the corresponding angular velocity of the motor can be calculated [16]. Kinetostatic analysis in quasi-static conditions allows finding the relationship between the external force axially applied to the load and the motor torque [27]. The radius of the string plays a pivotal role in the accuracy of the mathematical model. Traditionally, the model assumes a constant radius, yet more detailed studies have explored variations in radius as the string undergoes twisting [16]. Generally, as the string twists, its radius tends to increase due to the expansion of the resulting helix formed by the coiling string. Conversely, applying significant linear load forces will decrease the radius of the string.

Overview on TSA design. Studies have focused on evaluating the performance of various types of strings under different operational conditions, considering factors such as precision, maximum contraction, and lifespan. For instance, investigations have revealed that individual fibers within a non-braided string are prone to tearing or damage during twisting, whereas braided strings demonstrate greater resilience [9]. The longevity of strings has been examined across varying loads to understand their life cycles [9,167]. Moreover, variable stiffness can be achieved by adopting antagonistic configurations [168]. Examples of further developments are represented by the dual-mode TSA mechanism introduced in [54,94], enabling both speed mode with low contraction force and force mode with low contraction speed. These innovations broaden the applicability and versatility of TSAs in diverse contexts.

Overview on TSA control. Given that TSAs were introduced relatively recently in robotics and automation contexts, approximately two decades ago, its control still presents several open challenges. Feedback control of string contraction can be achieved by measuring contraction using a linear displacement sensor [76]. The controller then adjusts the motor torque to ensure that the measured contraction matches the desired contraction. However, in many instances, installing a sensor for linear displacement proves challenging due to the desired actuator flexibility and lightweight. To address this challenge, the kinematic model can be inverted to calculate the motor angle needed to obtain the desired contraction [4]. By regulating the motor angle to the desired value, the desired contraction can be achieved using simple motor encoder-based feedback control, eliminating the need for an external sensor. However, this method may exhibit limited repeatability and accuracy over long-term operation due to factors such as hysteresis, wear, and a creep of the strings. Hence, a combination of both approaches may be employed to mitigate their respective limitations [76]. Similarly, tension and impedance control can also be implemented [82].

Overview on TSA applications. TSA are particularly effective in engineering applications that require compact, lightweight, and high-force linear motion. One of their main uses is in robotics end-effectors (hands and grippers) [98]. TSAs are also employed in active prostheses, providing precise and energy-efficient movement control [115]. In addition, they are gaining attention in wearable devices, exoskeletons, and medical assistive technologies, where safety, flexibility, and silent operation are crucial.

The works discussing challenges that are still open and ongoing, regarding TSA technology, are summarized in Table 3, highlighting their advancements, benefits and challenges. In the following, we further provide a detailed discussion on recent and ongoing advancements in TSA technology, focusing on models, control strategies, materials, and applications, along with challenges and future directions.

7.2. Recent and ongoing advancements in TSA technology

TSA models and control. While most of the works on TSA model focus on kinematics analysis, for position control issues, recent studies are deepening string tension and force control issues, too, as proposed by Baek et al. [78]. Parameter identification of the mathematical model is needed for the design of efficient control strategies. The study proposed by Zallaghi et al. [37] aims at defining a simple but effective procedure for direct model parameters identification of TSAs, which accepts the model in the initial ODE-based form. The advancements enhance the understanding of TSA behavior and pave the way for improved model-based control strategies and more efficient selection of TSA motors. By integrating these advancements, future directions in TSA research may focus on further refining dynamic models, exploring novel control strategies, and expanding applications across various domains, from robotics to biomedical devices.

Furthermore, besides applications in rotational-to-linear transmission systems, recent works show how the complex, three-dimensional behavior of string twisting can be exploited for developing innovative mechanisms, for example for object grasping, as proposed by Long et al. [169].

Friction and lubrication. Overall, the studies on conducts presented in [7,22] and previously discussed, suggest that placing a TSA inside a conduit is feasible and holds potential for applications requiring high flexibility and mobility, as requested for example in wearable robotic applications discussed in Section 6. This is supported by the higher power transmission efficiency and inherently high gear ratio of TSAs with respect to other electromechanical transmission systems, enabling the use of more compact and less powerful motors, thereby reducing the overall weight and size of the actuation system.

Pre-twist. TSA can effectively transmit power even when the conduit is significantly deflected. However, issues such as pull-back, hysteresis, and chattering due to friction between the strings and the internal sheath of the conduit can appear in these cases. Recent advancements in TSA pre-twists have shown promising performance improvements, especially under high bending angles, as highlighted by Suthar et al. [28], who addressed two undesirable behaviors—pullback and chatter—that occur within conduits due to friction. The researchers introduced a dimensionless pre-twisting factor to quantify pre-twisting, allowing for controllable tuning parameters. Although this approach involves a trade-off in contraction stroke, the reduction remains within an acceptable range. Furthermore, they propose an online estimation method to dynamically determine the amount of pre-twist, achieving longer strokes compared to traditional offline techniques. In this context, the research is developing precise control schemes and advanced actuation systems incorporating multiple soft TSAs, promising enhanced performance and controllability.

Vibration effects. The impact of vibration on TSA within deflected conduits has been explored by Donghyee Lee et al. [170]. The experimental results reveal that applying vibration near the system's natural frequency during the final stages of the twisting and untwisting cycles significantly mitigates pull-back and hysteresis, and enhances string contraction. Specifically, when the sheath was deflected by 180° under a constant load of 3 kg, they observed a 70% reduction in pull-back and a 30% reduction in hysteresis compared to scenarios without vibration.

These findings highlight the potential of using vibration to improve TSA performance, offering a direction for future research to further refine and optimize the use of this type of actuation in applications where high bending angles are involved.

Materials. Recent advancements in pre-twists for TSAs have shown significant promise, particularly with the integration of shear-stiffening gels (STGs) [173]. A rotary motor combined with fibrous strings demonstrates excellent performance due to its power, lightweight, and large stroke capabilities. However, traditional twisted string transmission systems face limitations in stiffness range and force generation. To address these challenges, researchers have developed a variable stiffness artificial muscle by impregnating STGs into a TSA. This novel approach leverages high twisting speeds to produce large impact forces, which induce shear stiffening in the STG. This results in improved elasticity, stiffness, force capacity, and response time of the TSA. For instance, at a twisting speed of 4186 rpm, the elasticity of an STG-TSA reached 30.92 N/mm, compared to just 10.51 N/mm at a lower twisting speed of 200 rpm. Furthermore, the STG-TSA exhibited more significant shear stiffening under high stiffness loads, making it a promising solution for artificial muscles to coactivate with human muscles and enhance motion compensation.

Additionally, advancements in the durability of TSAs have been achieved through the development of a unique graphene-based composite coating. Twisted string actuators are widely used due to their mechanical simplicity and flexibility, yet their reliability under stringent conditions remains a concern. The primary issue is the increased wear of strings due to friction between fibers and strands, leading to a relatively short lifespan. To combat this, researchers have created a graphene-based composite coating for TSAs.

The graphene used in the coating was thoroughly analyzed using structural and chemical characterization methods, and the coated strings were examined with both spectroscopic and microscopic techniques [171]. Experimental studies showed that the newly coated strings had approximately double the lifetime of commercially procured coated strings. This development in graphene-based coatings holds the potential to significantly enhance the durability and performance of TSAs in future applications.

Recent developments on materials for TSA investigate the use of unconventional materials, for example, in [174] the magnetothermal properties of particular recycled materials are investigated for realizing

Table 3
Recent and ongoing advancements in TSA technology.

Category	Advancement	Details	Benefits	Challenges/Limits	References
TSA models	Improved TSA modeling	Focus on dynamic models. Direct parameter identification methods proposed for enhanced model accuracy	Better understanding of TSA behavior	Parameter identification requires robust methodologies and experimental validation.	[78]
TSA control	Improved TSA control mechanisms	Focus on string tension, and force control. Direct parameter identification methods proposed for enhanced control strategies.	Better understanding of TSA behavior, improved control strategies with more efficient motor selection.	Parameter identification requires robust methodologies and experimental validation.	[37]
Rotational-to-linear mechanisms	Exploitation of 3D twisting behavior for novel applications	Use of complex string behaviors for applications like object grasping.	Enables innovative TSA-based mechanism designs for diverse applications.	Complexities in accurately modeling 3D behavior under various conditions.	[169]
Friction and lubrication	TSA integration into conduits for wearable robotics	Higher efficiency and flexibility in power transmission. Compact, less powerful motors reduce actuator weight and size.	Enables flexible and mobile wearable robotics.	Friction-induced pull-back, hysteresis, and wear limit durability.	[7,22]
Pre-twist	Dynamic and online pre-twisting mechanisms	Introduction of dimensionless pre-twisting factor and online estimation methods to optimize stroke and performance.	Reduces pull-back and chattering, improves performance under high bending angles.	Trade-offs in stroke length due to pre-twisting.	[28]
Vibration effects	Use of vibration to enhance TSA performance	Applying vibration near natural frequencies reduces pull-back and hysteresis while improving string contraction.	Enhances stroke efficiency, particularly under high deflection and constant load conditions.	Needs precise vibration control systems for effective integration.	[170]
Materials	Integration of shear-stiffening gels (STGs) and graphene-based coatings	STGs improve elasticity and stiffness. Graphene coatings double TSA lifespan by reducing wear and friction.	Improved TSA durability, enhanced performance under high loads, and increased lifespan.	Limited adoption due to cost and scalability of advanced materials.	[171]
Self-sensing TSAs	Development of compliant, self-sensing TSAs	Use of thermally activated, conductive polymer strings for intrinsic position sensing and actuation.	Enables compact, adaptive, and sensor-free TSA-driven systems.	High complexity in material synthesis and integration with control systems.	[11,35]
Non-linear pulleys	Variable-radius pulley systems	Innovations like Elastomeric Continuously Variable Transmission (ElaCVT) improve TSA adaptability for robotic joints.	Expands TSA application scope, improves actuator functionality.	Complexity in integrating nonlinear systems with TSA mechanisms.	[49]
Challenges	TSA limitations in stroke, speed, durability, and scalability	Issues include material wear, slack in bidirectional TSAs, and complexities in control and manufacturability.	Opportunities for innovation in material design and control systems.	Requires significant material and mechanical improvements to overcome fundamental TSA limitations.	[16,171,172]

soft tendon-based actuators. In [175] the electrical properties of silver-plated yarns are investigated, and the authors point out that such materials can be employed in TSA strings to provide them sensing capabilities.

Life cycle. A comprehensive study on the lifespan of Twisted String Actuators (TSA) by evaluating string durability under various experimental conditions [9,176]. These included different motor speeds (1500 and 2500 rpm), loads (9 kg and 25 kg), stroke lengths (10% and 20% of the untwisted string length), and string diameters (1 mm and 1.5 mm). Specifically, the experiments were performed at a motor speed of 2500 rpm, a stroke of 20% (50 mm), and loads ranging from 9 kg to 25 kg.

Fourteen types of Dyneema strings from four manufacturers (Armare, Gottifredi, Liros, and Alpha Ropes) were tested, varying in type and diameter. The study measured the lifespan of these strings under the given conditions. Dyneema, a readily available string material, demonstrated the longest lifespan, with Liros achieving 59,956 cycles (88.2 h) for a string diameter of 1.5 mm and 129,271 cycles (178.1 h) for a diameter of 2.0 mm under a 9 kg load.

Notably, Liros strings (1.5 mm and 2.0 mm) recorded the longest lifespan under a 9 kg load. Gottifredi's Evofly78 string showed the second-longest lifespan at 47,423 cycles with diameters of 1 mm to 1.6 mm. Another string from Gottifredi, SK78, recorded 121,942 cycles for a 2.0 mm diameter under a 9 kg load. For higher loads (15, 20, and 25 kg), Gottifredi's Evofly78 and SK78 demonstrated the longest lifespans.

Despite these findings, further research is necessary to enhance TSA lifespan under diverse material compositions and coatings. Key areas of investigation include improving internal resistance, mitigating string heating, assessing the impact of twisting direction and braiding techniques, and comparing string dimensions. Additionally, the potential benefits of lubrication and coating methods for extending TSA lifespan warrant further exploration.

Self-sensing. TSAs have been utilized in various robotic applications. However, their integration into soft robotics has still faced significant challenges. Primarily, conventional TSAs rely on stiff and non-compliant strings, limiting their adaptability in soft robotic systems. Moreover, precise control typically necessitates external position or force sensors, resulting in rigid and bulky TSA-driven robots.

Recent research by Bombara et al. [11] proposes a novel TSA design, modeling, and implementation approach to address these limitations. Their study introduces compliant TSAs capable of generating substantial strain and self-sensing during actuation. This innovative design replaces traditional stiff strings with compliant, thermally activated, and conductive supercoiled polymer strings. Experimental results demonstrate the promising performance of these advanced TSAs, boasting a normalized stiffness of less than 50 N, strain exceeding 30%, and intrinsic position self-sensing capabilities during twisting. Moreover, the quasi-static actuation and self-sensing properties are effectively characterized using Preisach hysteresis operators, encompassing both twisting-induced and thermally induced actuation mechanisms.

Hosseini et al. [177,178] present the integration of TSA with a force sensor based on optoelectronic components. Cho et al.in [179] present the integration of a single-axis load cell into TSA strings, for tension measurement. Sensor integration is realized by infusing an uncured polymer into a small portion of the string, while a liquid-metal thin-film soft sensor is externally connected. As the cable is subject to a tensile strain, the liquid-metal electrical resistance varies, providing information on the tension value. In the paper, the authors verify that the sensor shows a linear behavior in the range 5–100 N with negligible hysteresis.

These advancements pave the way for more agile, adaptable, and compact TSA-driven robotic systems, with implications extending to various fields, including soft robotics, prosthetics, and wearable technologies. Looking ahead, future directions may explore further enhancements in compliance, sensing accuracy, and integration with advanced control strategies to unlock the full potential of TSA technology in next-generation robotics.

Non linear pulleys. There is a need to enhance the applicability of TSA-based mechanisms to robot joints with single actuators, necessitating the development of supplementary mechanisms like tensioners. These advancements will expand the scope of application and optimize the functionality of the variable-radius pulley in TSA, paving the way for more efficient and adaptable robotic systems.

Solutions such as the Elastomeric Continuously Variable Transmission (ElaCVT) proposed by Kim et al. [56] and previously introduced pave the way for enhanced functionality and versatility in robotic applications, promising further innovation and refinement.

Challenges and limitations. Notwithstanding the opportunities and potentiality previously described, TSAs face several mechanical limitations, including force output, stroke output, speed, and durability. Unidirectional TSAs have a limited stroke, while bidirectional TSAs can suffer from slack and force-fighting issues. The use of antagonistic TSA actuation with non-linear pulley designs adds to these challenges. A significant limitation is the limited life cycle of TSAs, as material degradation and fatigue phenomena can drastically reduce their longevity. This issue has been explored in studies such as those by Gaponov et al. [167], Usman et al. [9], and Sadachika et al. [180], which highlight how friction between strings contributes to wear and overheating, thereby reducing the actuator's reliability. To address these problems, Zhao et al. [172] developed a coating system to maintain appropriate temperatures in soft robots using TSAs, while Sarkar et al. [171] proposed a graphene-based coating to reduce wear. Furthermore, TSAs face challenges in control and sensing complexities, as well as scalability and manufacturability issues. In TSA along guided surface configurations, pre-twisting can eliminate pull-back and chattering but at the cost of losing a 50% contraction of the untwisted string length, illustrating the trade-offs involved in optimizing these systems.

7.3. Future directions and opportunities

The future of TSAs is set for significant advancements, particularly through the development of new materials and fabrication techniques. The creation of compliant materials specifically designed for soft robotic applications will enhance the flexibility, adaptability, and durability of TSAs. These improvements will enable more complex and nuanced movements in diverse environments, broadening the range of applications for soft robots.

One transformative leap in TSA technology is the integration of self-sensing capabilities, which will allow actuators to monitor their own performance in real time. This advancement will lead to more precise and reliable operations, facilitating the development of advanced feedback systems in robotics that improve efficiency and responsiveness. The ongoing exploration and refinement of these materials and techniques will not only expand the practical applications of TSAs but also drive innovation in sectors ranging from medical devices to wearable technology and beyond.

Most current research on TSAs focuses on avoiding overtwisting and coiling after regular twisting due to their unpredictability and control challenges. Anyway, exploiting TSA behavior during overtwisting phase represents an opportunity to extend the limits of this type of actuation. Tavakoli et al. [32] identified two phases of TSA behavior: twisting and overtwisting, and proposed a mathematical model for both. Exploiting these two phases can achieve high contraction percentages, up to 81%. Additionally, Konda et al. [181,182] proposed a method for obtaining a regular overtwist pattern, which increases the TSA stroke. These insights suggest that future research could explore how to effectively use TSAs in series and parallel configurations to design artificial muscles.

The development of robust control strategies for TSAs presents several promising future directions and opportunities. Enhancing the precision and reliability of TSAs in variable and dynamic environments is crucial for applications in robotics and prosthetics. Integrating advanced sensors and real-time feedback systems can improve control accuracy and adaptability. Leveraging machine learning algorithms to predict and compensate for non-linear behaviors and wear over time could significantly extend the operational lifespan and performance consistency of TSAs.

Exploring new materials and hybrid actuator designs can contribute to more efficient and durable solutions. The miniaturization of control systems will enable the incorporation of TSAs into smaller, more compact devices, expanding their applicability in fields such as medical devices and consumer electronics. Collaborative efforts across disciplines, including materials science, mechanical engineering, and computer science, will be essential to drive innovation and practical implementations of these advanced control strategies.

8. Conclusion

Twisted String Actuators (TSAs) represent a promising and versatile technology in numerous robotics fields, offering significant interesting design and application solutions. Since their introduction to robotics is rather recent, a consistent part of the research is devoted to their modeling and mathematical simulations and on their design opportunities. However, they are currently spreading in different robotic applications and the control aspect is subject of interesting and promising studies. This review has highlighted the developments in TSA technology, showcasing their potential in various applications, including robotics, prosthetics, wearable and medical devices. The innovative approaches to TSA design, such as the integration of self-sensing capabilities and the use of advanced materials, have paved the way for more flexible, adaptable, and durable actuators. These advancements are essential for achieving more complex and precise movements in diverse environments.

However, the journey toward fully realizing the potential of TSAs is fraught with challenges. Mechanical limitations, such as force output, stroke length, and durability, continue to pose significant hurdles. Issues like unidirectional stroke limitations, slack in bidirectional configurations, and the wear and tear associated with material fatigue require ongoing research and development. The integration of robust control strategies and advanced sensors is crucial to overcome these limitations and to improve the precision and reliability of TSAs under dynamic and variable conditions.

Future directions in TSA research promise exciting opportunities. The development of new materials and fabrication techniques will further enhance the capabilities of TSAs, enabling their use in a wider range of applications. Leveraging artificial intelligence and machine learning algorithms to predict and compensate for non-linear behaviors and material wear will extend the operational lifespan and improve performance consistency. Additionally, the miniaturization of control systems will facilitate the incorporation of TSAs into smaller, more compact devices, expanding their applicability in medical and consumer electronics.

CRediT authorship contribution statement

Monica Malvezzi: Writing – review & editing, Writing – original draft, Visualization, Supervision, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Bhivraj Suthar:** Writing – review & editing, Writing – original draft, Visualization, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Mihai Dragusanu:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization.

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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.

Data availability

No data was used for the research described in the article.

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