Mechatronics 98 (2024) 103141

Contents lists available at ScienceDirect

Mechatronics

journal homepage: www.elsevier.com/locate/mechatronics

MGlove-TS: A modular soft glove based on twisted string actuators and flexible structures ☆,☆☆

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ARTICLE INFO

Keywords:
Soft actuated glove
Twisted string actuators
Robotic rehabilitation

ABSTRACT

Advances in technology, design, and manufacturing processes are leading to noticeable improvements in rehabilitation management. In this paper, we introduce MGlove-TS, an actuated soft glove based on twisted string actuators (TSAs) developed to assist and support individuals with hand impairments limiting active movements and grasping force in their rehabilitation process and in daily living. The glove is designed to be lightweight, portable, easy to wear and use, comfortable for prolonged periods, with a little encumbrance, flexible and adaptable, and highly modular. The paper presents the main features of the proposed glove and a prototype actuating the thumb and index finger in flexion/extension and adduction/abduction movements. The actuated glove prototype has been evaluated through a series of tests, whose results showed its potential usefulness.

1. Introduction

Studies carried out by public health institutions, for instance, the World Health Organization (WHO), show a growing trend for people's longevity: in 2019 on average people were living more than 6 years longer than in 2000, but, on average, only 5 of those additional years were lived in good health. The same studies also showed a worrying increase in disability and consequently the need for assistive and rehabilitation tools.

Advances in technology, design and manufacturing processes, and materials are leading to noticeable improvements in the management of rehabilitation and in the related economic burden [1,2]. Notwithstanding the promising development, there are still some socio-economic challenges that limit robotic device uptake in healthcare, assistive, and rehabilitation contexts, despite their high technical maturity [3]. Significant improvements are still needed to meet the predicted rise in the number of stroke survivors and improve care quality.

Assistive and rehabilitation technology has become an important research area for improving the quality of life for people with disabilities or age-related limitations. Among various assistive resources, devices for the upper limbs and hands, and in particular exoskeletons and actuated gloves have received attention as a potential solution for rehabilitation and assistance in activities of daily living. However, designing assistive gloves with sufficient dexterity and adaptability to user-specific needs is still an open challenge [4].

Researchers have explored various approaches for designing assistive gloves using different actuation technologies, such as shape memory alloys, pneumatic systems, and electric motors [5–7]. However, these approaches often suffer from limitations such as high cost, complexity, lack of adaptability, and flexibility. Flexible and lightweight actuators have been explored as a promising technology for designing gloves for assistive and rehabilitation tasks [8]. In particular, twisted string actuators (TSAs) are one of the available technologies that have shown interesting potential in wearable devices. For instance, in [9] TSAs are used in hip exoskeleton in lifting tasks, while [10–13] represent some examples of TSA-based elbow exoskeletons. TSA-based actuators offer several advantages over traditional actuators, including a high power-to-weight ratio, low cost, and simplicity of fabrication and control. Additionally, TSAs can generate a linear with high accuracy

☆ We acknowledge the support of the European Union by the Next Generation EU project ECS00000017 "Ecosistema dell''Innovazione" Tuscany Health Ecosystem (THE, PNRR: Spoke 9: Robotics and Automation for Health).

☆☆ This paper was recommended for publication by Associate Editor Kyoungchul Kong.

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https://doi.org/10.1016/j.mechatronics.2024.103141
Received 1 August 2023; Received in revised form 28 November 2023; Accepted 22 January 2024
Available online 29 January 2024

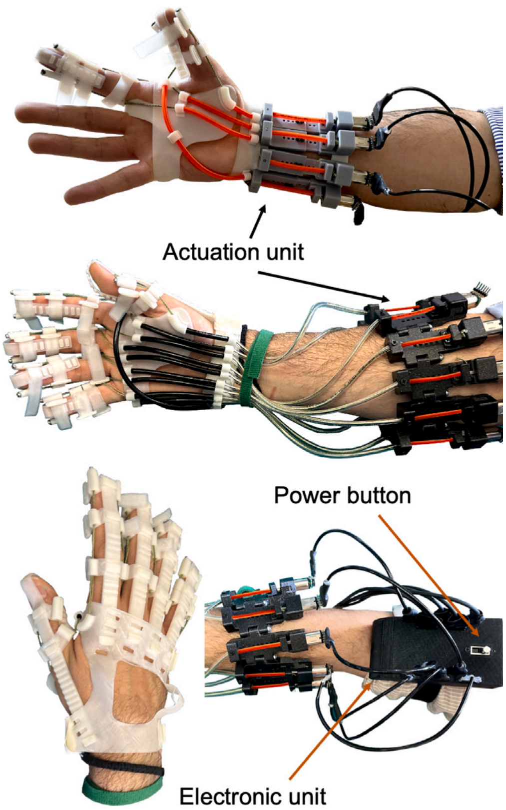


Fig. 1. MGlove-TS prototypes. Top figure: partial glove with the thumb and index finger actuation only. Middle and bottom images: different views of the complete implementation worn by a user.

and repeatability, making them suitable for precise finger movements in assistive gloves.

In this paper, we present the design, development, and preliminary testing of MGlove-TS, an actuated glove driven by TSAs with a flexible passive structure (Fig. 1). The glove is designed to assist in grasping and releasing objects by supporting the user's finger movements and force, and in realizing rehabilitation exercises. TSAs and a system of tendons properly routed activate the hand's joint motion, while a compliant passive structure is used to reduce the stress on the fingers, prevent excessive pressure on the grasped object, and recover hand rest position when TSAs are released. The glove is designed to be lightweight, flexible, and comfortable to wear for long periods.

The device proposed in this paper builds upon previous work on TSAs for wearable devices, such as the hand exoskeletons presented in [14–18]. In particular, in [14] a TSA-based glove for haptic applications is presented, while in [19] an active hand orthosis is presented. With respect to the existing solutions, in which a single tendon per finger is adopted, MGlove-TS uses two actuated tendons per finger combined with a passive flexible structure so that both the flexion/extension and abduction/adduction motions are actuated, while the passive structure is designed to compensate for the intrinsic underactuation of the system, allowing the closure motion generated by the tendons in flexion motion to be harmonized with hand joint natural motion. The passive element is needed also to support the extension motion. The compliant structure is realized with Flex-45 thermoplastic co-polyurethane, a soft but resistant material that allows the glove to be light and comfortable.

The design of MGlove-TS is modular and parametric. The modularity is realized by developing independent elements for the thumb and for the fingers, which can be combined together realizing a complete glove or partial devices. In this paper in particular we present the prototypes of a complete implementation and a partial implementation involving the thumb and the index only (Fig. 1). The complete implementation is presented to verify system wearability and portability, while the partial one is used for the fingertip and motion tests to verify and characterize the motion capabilities of the individual thumb and finger units.

The design of the glove is parametric so that the design can be easily customized by regulating a limited set of variables only. The design, development, and preliminary validation of the device was carried out in collaboration with a potential user who contributed to the definition of design requirements, participated in the design and prototyping phase, and contributed to the preliminary testing and evaluation, following a user-centered design process [20,21].

The paper is organized as follows. In Section 2 the main design requirements for the proposed MGlove-TS are introduced. In Section 3 kinematic evaluations are reported meanwhile Section 4 describes the proposed glove, focusing in particular on its hardware and actuation part. In Section 5 the results of a set of experiments are presented. Section 6 discusses the obtained results and presents a comparison with other solutions available in the literature, while Section 7 concludes the work.

2. Device main requirements

This paper presents an actuated soft glove developed for rehabilitation and training and as an assistive device for people with upper limb and hand impairments reducing the hand active range of motion and grasp force. A user-centered design process was adopted for the design and development of MGlove-TS: the requirements for the design were defined taking into account the needs highlighted by a potential user that actively participated in the development process and the preliminary evaluation phase, providing feedback and suggestions that contributed to refining and adjusting the initial design.

Application contexts. The design process has been developed following an impairment-guided approach, as suggested in [22]. The system has been developed as a rehabilitation and training tool for patients with low active control of the hand, a low residual force, low muscle tone, and low spasticity, that could be caused by different neurologic conditions (e.g. stroke, Parkinson's disease, Limb-Girdle Muscular Dystrophy, etc.). The device described in this paper, in particular, is tailored to the needs and requirements of a representative user. The modular structure of the actuated soft glove allows different glove configurations, so that the user can decide to use partial configurations, as for instance the thumb and index module only, or all finger modules. Furthermore, the modular and parametric structure makes the proposed solution adaptable to different subjects with different needs.

Kinematic requirements. As a general requirement, the range of the motion actuated by the glove should be as wide as possible to support the hand in all its possible tasks and rehabilitation exercises, but absolutely not wider than the physiological values, to avoid unsafe and painful situations [23].

Each finger of the human hand is usually schematized as a serial 4-DoFs kinematic chain, with one 2-DoFs for the metacarpo-phalangeal (MCP) joint (modeled as a universal joint, realized by two intersecting, orthogonal revolute joints) and two 1-DoF joint for the proximal (PIP) and distal (DIP) interphalangeal joints. In most of the biomechanics models of the human hand, if the hand is not affected by any pathology, the rotation axes of PIP, DIP, and the flexion/extension axis of the MCP can be assumed approximately parallel. The thumb has a more complex structure that can be modeled as a kinematic chain with at least 5-DoFs: 2-DoFs in the trapezio-metacarpal (CMC) joint, 2-DoFs in the MCP joint, and 1-DoF in the interphalangeal (IP) joint. Concerning the TM joint, which allows thumb opposition, the base of the metacarpal connected to the thumb is saddle-shaped and articulates with the trapezium

Table 1
Active range of motion (AROM) for hand joints, average values for an adult, healthy hand (average values between male and female subjects adapted from [24]).

Thumb	Joint	Max. value	Index	Joint	Max. value
Flexion	CMC	45°–50°	Flexion	MCP	85°–90°
	MCP	50°–55°		PIP	100°–115°
	IP	85°–90°		DIP	80°–90°
Extension	IP	5°	Extension	MCP	30°–45°
				DIP	20°
Add./Abd.	MCP	60°–70°	Add./Abd.	MCP	20°–30°

bone. The resulting joint has two non-orthogonal and non-intersecting rotation axes.

Functional active range of motion (AROM) of hand joints depends on the subject's age, gender, and health conditions and is widely documented in medical, physiotherapy, and rehabilitation references, as reported for instance in [24,25]. For the sake of completeness, we reported in Table 1 the average values of hand joint AROM for an adult, healthy hand, obtained from [24]. These values have been considered as references for the design of the device. During the execution of rehabilitation exercises and in assistive tasks, of course, hyperextension of all the joints should be carefully avoided. Concerning dynamics requirements, physiotherapists suggest that the time for a complete flexion/extension cycle should be lower than 20 s, while data for adduction/abduction motions are less demanding [26].

Force requirements. The glove is designed to be used in rehabilitation and training tasks but it can be used also as a grasp assistive system that provides additional force to the user's fingers during object grasping. The design of the glove will allow for a secure grip on a variety of objects, including those with irregular shapes. The glove will also provide enough force to hold objects without causing discomfort to the user. Li et al. [27] underline that in grasp tasks, the forces required at the fingertips are typically below 20 N. Smaby et al. [28] presents a detailed analysis of pinch forces, underlining that the pinch force can vary in the range 0–30 N, even if in most of the applications the pinch force is about 10 N.

Sensing and control. The glove will be equipped with sensors to detect the user's hand movements and provide her/him feedback. This feedback can include visual or auditory cues to guide the user's exercise movement. This paper focuses in particular on the device's mechatronic design rather than on its control. Regarding this aspect, according to our previous experience [4], we assume to be able to control each unit (thumb and fingers) both independently and in a coordinated way using a properly defined user interface. Inertial and magnetic sensor-based motion capture systems will be integrated into MGlove-TS in the next development of this work for complete tracking of hand posture [29] and a more reliable system control. The device will be able to perform some pre-defined exercises, for instance, flexion/extension, adduction/abduction of the thumb or single fingers, or to perform coordinated motions, for instance, precision or pinch grasp, power grasp, etc. For rehabilitation and training exercises, each actuator is controlled in position. The overall device control scheme will have a structure similar to the one described in [4].

Wearability, adaptability, and modularity. The glove should be designed to fit comfortably and securely on the user's hand with minimal interference to natural hand movements. The glove should also be lightweight and flexible to avoid restricting the user's hand movement. The glove should have a reliable power source that can provide sufficient power for the actuation mechanism and sensors. The power source should be lightweight and portable to allow for use in daily living activities. The battery life should be enough long to allow the wearer to use it for extended periods of time without needing to recharge. Batteries are typically one of the more critical elements in wearable devices due to their mass and encumbrance. As a trade-off between a suitably long activity and a limited battery weight and encumbrance, a reasonable duration of battery life is 45 min, corresponding to the duration of a standard physiotherapy session.

The assistive glove will be adaptable to meet the specific needs of the user. It will allow for adjustments to the grip strength and finger length, to accommodate individual preferences and requirements. The users will be able to decide to wear all the modules or only a subset of them (for example, one finger only, the thumb only, or the index and the thumb, or the complete hand, etc.), according to their needs.

The assistive glove should be user-friendly, easy to put on and take off, and simple to operate. It should not require extensive training or specialized knowledge to use. Socio-economical aspects are important to be considered when developing robotic devices for assistive and rehabilitation tasks [30], since excessive costs limit the potential adoption of such devices. Therefore, the glove should be affordable and accessible to a wide range of users, including those with limited financial resources. The glove must be designed to withstand daily wear and tear, as it will be used regularly. It should be made from high-quality materials that can withstand repeated use and exposure to various environments. The glove should also be easy to clean and maintain.

3. Preliminary evaluations

This section presents some preliminary considerations on the kinematic and dynamic relationships between motor rotation and finger movements. In particular, this section seeks to draft the kinematics relationships between motor rotation and finger movement. Due to the deformable structure of the proposed glove, a reliable mechanical model relating hand movements to motor actuation is difficult to define, since it depends on several parameters, that further depend on the user's specific characteristics. However, a basic model based on simplifying assumptions is useful to define some design criteria, for instance where the tendons should be guided, and the size of the motors to be used for the TSA.

3.1. Finger actuation

Each of the fingers can be modeled as a 3-links, 4-DoFs kinematic chain, in which the MPC joint can be represented as a Universal (U) joint corresponding to two revolute (R) joints with orthogonal and incident axes, while PIP and DIP joints can be represented as revolute (R) joints. The axes of the three R joints defining the flexion/extension motion can be considered approximately parallel. To activate both the flexion/extension motion and the adduction/abduction movements of the finger, the tendons are connected as shown in Fig. 2(a). The tendons are fixed at the fingertip and pass along the two lateral parts of the finger, through guides realized on ring elements connected to the proximal and intermediate phalanges. When the finger is completely extended, the tendons are ideally on the coronal plane and are symmetric with respect to the finger axis.

Pulling the tendons with different lengths, i.e. $\Delta x_{f1} \neq \Delta x_{f2}$ activates an abduction/adduction movement. Let us indicate with d_{PP} the distance between the tendon's routing guides on the proximal phalanx, with d_{MC} the same distance close to the MCP joint, and with l the distance between the routing guides on the proximal phalanx and close to MCP joint. To have an abduction/adduction θ_{f1}, it is necessary that the TSAs are activated with the following displacements (inverse kinematics):

$$\Delta x_{f1} = \sqrt{l^2 + \left(\frac{d_{MC} - d_{PP}}{2}\right)^2} - \sqrt{l_f^2 + \left(\frac{d_{MC}}{2}\right)^2 - l_f d_{MC} \cos\alpha}, \quad (1)$$

$$\Delta x_{f2} = \sqrt{l^2 + \left(\frac{d_{MC} - d_{PP}}{2}\right)^2} - \sqrt{l_f^2 + \left(\frac{d_{MC}}{2}\right)^2 - l_f d_{MC} \cos\beta}, \quad (2)$$

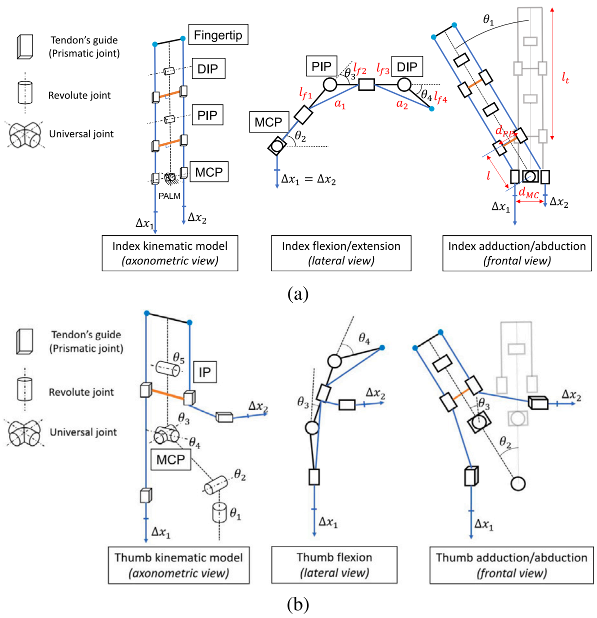


Fig. 2. Biomechanic and glove actuation schemes. (a) Index finger. (b) Thumb..

where:

$$\alpha = \pi/2 - \theta_1 - \arcsin\left(\frac{d_{PP}}{2l}\right),$$

$$\beta = \pi/2 + \theta_1 - \arcsin\left(\frac{d_{PP}}{2l}\right),$$

$$l_f = \sqrt{l^2 + \left(\frac{d_{PP}}{2}\right)^2}.$$

The relationship between abduction/adduction rotation angle θ_{f1} and tendon strokes (direct kinematics) is:

$$\theta_{f1} = \arcsin\left(\frac{\Delta x_{f1} - \Delta x_{f2}}{d_{PP}}\right). \tag{3}$$

Pulling/releasing the tendons with the same lengths, i.e. $\Delta x_{f1} = \Delta x_{f2}$ activates a flexion/extension movement of the finger. Let us indicate with θ_{f2}, θ_{f3}, θ_{f4} flexion angles of MPC, PIP and DIP joint, respectively. In this case, the direct kinematics relationship cannot be defined unless a constraint between θ_{f2}, θ_{f3}, and θ_{f4} is established, for instance by considering the ratios defined by [31], or by means of the postural synergies defined by [32]. On the other hand, the inverse kinematics relationship can be easily defined given the lengths of the phalanges and the distances between the tendon routing guides and hand joints (see Fig. 2(a)), in particular

$$\Delta x_{f1} = \Delta x_{f2} = l_t - a_1 - a_2, \tag{4}$$

where l_t is the distance between the fingertip and the tendon routing guide on the proximal phalanx, while a_1 is the distance between the tendon routing guides in the flexed configuration, depending on θ_{f3} according to the following relationship:

$$a_1 = \sqrt{l_{f1}^2 + l_{f2}^2 + 2l_{f1}l_{f2}\cos\theta_{f2}}, \tag{5}$$

and a_2 is the distance between the tendon routing guide on the intermediate phalanx and the fingertip, depending on θ_{f4}, according to the following relationship:

$$a_2 = \sqrt{l_{f3}^2 + l_{f4}^2 + 2l_{f3}l_{f4}\cos\theta_{f4}}. \tag{6}$$

3.2. Thumb actuation

The kinematic structure of the thumb is more complex with respect to the fingers. As previously introduced, in the CMC joint the contact between the metacarpal and trapezium bones has a saddle shape that from the mechanical point of view could be represented as two R joints with non-orthogonal, non-incident axes. The MPC joint can be represented similarly to the finger as a U joint, while the IP joint can be represented as an R joint. In this work, we choose to actuate the flexion-extension motion (generated by the MPC and IP joints) and the adduction/abduction motion (generated mainly by the CMC and more limited by the MPC). A scheme of the thumb structure and actuation system is shown in Fig. 2(b).

Actuating the thumb is further complicated by the limited space available for tendon routing guides. In this work, we used two tendons to actuate the thumb, both fixed at the fingertip and passing through the lateral part. Two symmetric guides are placed along the proximal phalanx, the external tendon is then routed along the thenar muscle, while the internal is routed along the adductor muscle, between the thumb and the index. The actuation structure is therefore non-symmetric. Direct and inverse kinematics relationships are in this case more complicated, due to the structure of the thumb and actuation asymmetry.

3.3. Inverse kinematics evaluations for the index and the thumb

In the previous subsection, we analyzed simple adduction/abduction and flexion/extension motions only, however, in principle, by properly controlling TSA strokes more complex movements can be reproduced. To evaluate this possibility, the kinematic scheme of MGlove-TS has been implemented in Syngrasp Toolbox [33]. The 20-DoF model of an anthropomorphic hand, already implemented in the toolbox has been employed. The model is also referred to as the paradigmatic hand and its characteristics are detailed in [34,35].

On the hand model, points corresponding to TSA string routing on the phalanges and the palm have been defined, as previously defined (see Fig. 2). For each motion, the displacements of the MGlove-TS characteristic points are tracked (specifically, the fingertips and the tendon guides). On the basis of such displacements TSA stroke values during closure motion can be defined. These simulations showed that besides simple flexion/extension and adduction/abduction exercises, more complex movements can be realized with the actuated glove. These preliminary simulations showed also that the maximum stroke that is needed for the actuators to perform a wide set of exercises is lower than 20 mm.

3.4. Twisted string actuators

The TSA consists mainly of a small DC motor, and two strings attached around the motor shaft. During twisting, the strings are wound at a helical angle resulting in a linear motion. The scheme of the TSA module realized for the glove is shown in Fig. 3(a).

To introduce the basic mechanical characteristics of the TSA, in this section we report the main kinematics and force relationships, developed on the basis of the studies presented in [36–38]. Based on the scheme in Fig. 3(a), let us define the length L_0 as the distance between the motor shaft and the end delimited twisted strings (TS) part. As the strings are fixed around the motor shaft, they diverge at the end with a radius A, i.e. the helix radius. Let us indicate with $L = \sqrt{L_0^2 + A^2}$, and r_{string} the strings length and radius, respectively. When the motor rotates the strings wind up in a helix, causing a contraction Δx, that depends on motor rotation θ according to the following relationship:

$$\Delta x = \sqrt{L^2 - A^2} - \sqrt{L^2 - A^2 + (\theta(r_{string} + A))^2}. \tag{7}$$

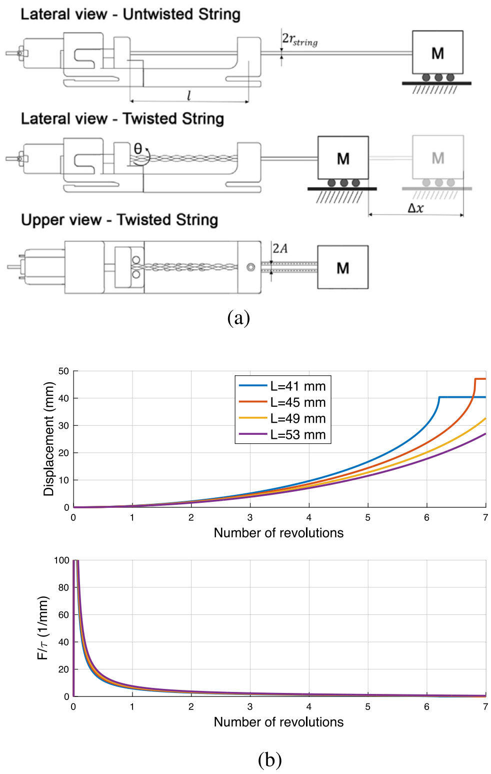


Fig. 3. Twisted String Actuator scheme and kinematics and statics evaluations. (a) Scheme of the TSA module. (b) Numerical evaluation of the TSA kinematics (displacement Δx vs number of motor revolutions) and statics (ratio F/τ as a function of the number of revolutions) relationships.

The helix angle can be evaluated as

$$\alpha = \sin^{-1}\left(\frac{\sqrt{L^2 - (A+\theta r_{string})^2}}{L}\right). \tag{8}$$

Using the Principle of Virtual Works, neglecting any form of friction, the relationship between the motor torque τ_{motor} and the pulling force F can be defined as follows

$$\frac{F}{\tau} = \frac{\sqrt{L^2 - (A+\theta r_{string})^2}}{r_{string}(A+\theta r_{string})}. \tag{9}$$

By assuming that all the strings have the same length and are made of a material characterized by Young's modulus E, the tensile stiffness can be evaluated, for each string, as

$$k_s = \frac{\pi E r_{string}^2}{L_s},$$

where L_s is the length of the string when no loads are applied to it. Assuming that all the strings in the TSA are equally stretched when a load F is applied to it, the stiffness of the TSAs can be calculated as follows

$$K_{TSA} = n k_s \left(1 - \frac{(A+\theta r_{string})^2}{L^2}\right). \tag{10}$$

Usually, the stiffness of the strings should be considered when evaluating TSA's dynamics characteristics. In the application described in this paper, however, since each single Dyneema string, used for the prototype, has a stiffness around 40 kN/m [38], we assumed not to consider the elongation effect due to the load.

Fig. 3(b) reports the results of TSA kinematics evaluation obtained with $r_{string} = 0.3$ mm, $A = 1.5$ mm and $L \in \{41 : 4 : 53 \text{ mm}\}$, which are the parameters that are used for the TSA modules of the presented actuated soft glove prototype.

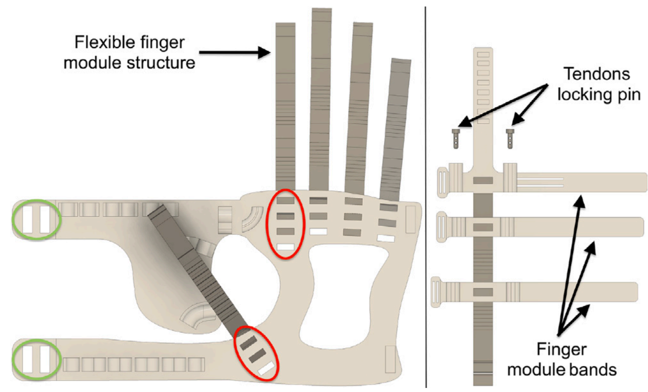


Fig. 4. Soft-Glove 3D-CAD model. The lower part wraps the user's palm. The thumb and index finger modules have a compliant structure. Green and red circles highlight the parts that allow adjusting the soft glove according to the user's needs.

The maximum motor angle to prevent tendon overtwisting can be evaluated as [36]:

$$\theta_{max} = \frac{\pi L - A\sqrt{\pi^2+4}}{r_{string}\sqrt{\pi^2+4}}. \tag{11}$$

The TSA, above this value, presents great non-linearity and high hysteresis.

3.5. Approximations and limitations

The aim of this section is to illustrate the principles that guided the design and development of the glove, in particular the actuated movements for the thumb and for the fingers, and how such movements can be actuated by tendons. We also described some mathematical relationships for direct and inverse kinematics for the actuated hand and for the TSA. It is worth underlining the approximations and limitations of such relationships. Kinematics equations relating hand configuration to actuators' strokes depend on parameters characteristics of the specific subject wearing the actuated soft glove (e.g. length of the phalanges, finger width), but also on how the glove is worn (e.g. position of the routing guides). Since the finger tissues where the guides are fixed are not rigid, such parameters can vary for the same subject in different wearings and during the same session. Furthermore, the hand model has been defined on the basis of some assumptions, for instance, that the axes of the flexion joint are parallel.

The presented model was aimed at defining the preliminary hardware characteristics of the device and cannot be directly adopted for defining its control parameters, due to the uncertainties and variability of several elements that could affect system reliability. The evaluation of the system performance with respect to such aspects and its robustness with respect to uncertain and variable parameters should be further assessed, also by means of experimental measurements. Furthermore, to set control parameters, a suitable calibration procedure is needed at the beginning of each training and rehabilitation session.

4. Device description

MGlove-TS consists of a soft-glove and an actuation and control unit worn on the forearm. In this section, we present two prototypes of the proposed system in the first one the thumb and the index finger only are actuated, while in the second one all the fingers and the thumb are actuated. The actuated glove worn by the user is shown in Fig. 1, while the CAD model of the unworn soft glove is represented in Fig. 4.

Table 2
Main technical specifications and characteristics of TSA-actuated Soft Glove.

Item	Specifications
MGlove-TS specifications	
Weight with actuation	0.375 [kg]
Material type	TPU Flex-45
Modular	Fingers, thumb
Motion type	flexion/extension, abduct./adduct.
Tip force	18 [N]
Controller size (W × H × D)	62.3 × 18 × 10 [mm]
TSA specifications	
Range TS zone	41-53 [mm]
Cable diameter	0.6 [mm]
Cable material	Dyneema polyethylene
DC motor specifications	
Size (W × H × D)	10 × 12 × 26 [mm]
Weight	9.5 [g]
No-load speed @ 6V	1100 [rpm]
Stall current @ 6V	1.5 [A]

The glove consists of a part that wraps around the hand palm and a series of independent modules, one for each finger. The user can choose how many and which fingers have to be actuated. The modules are actuated by tendons combined with twisted strings (TS).

The actuation system within the prototype, responsible for enabling soft movements of the fingers, relies on the deployment of up to ten brushed DC motors, two for each thumb or finger unit. More specifically, this setup involves, for each actuator, a pair of tendons passing through flexible PTFE tubes. At one end the tendons are securely attached to the shaft of their corresponding DC motor, while at the other end, they connect to the respective tip of a finger or the thumb. These pairs of DC motors induce twisting motion in the tendons, resulting in the contraction of the cables and thereby constraining the fingers to perform flexion/extension or adduction/abduction movements. We employ 30:1 Micro Metal gear motors, which are characterized by their robust carbon brushes and an extended motor shaft, sourced from Pololu Corporation, USA. Each DC motor boasts a maximum stall torque of 0.044 Nm and can achieve a peak angular speed of 115.19 $\mathrm{rad/s}$. The motors were chosen for their suitability in realizing the Targeted Soft Actuation (TSA) [39], attributed to their low voltage requirements, remarkably lightweight, portable, and compact. A comprehensive overview of the primary technical specifications for the twisted string actuation system can be found in Table 2.

The Micro Metal DC motors come equipped with magnetic encoders, courtesy of Pololu Corporation, USA. These encoders rely on a magnetic disc and a Hall effect sensor to supply precise position feedback, generating 12 counts per revolution of the motor shaft. To facilitate seamless motor control, these encoders are interconnected with a compact driver (DRV8835, by Pololu Corporation, USA), which interfaces directly with the motors through the controller, which is a Teensy 3.6 based on an ARM Cortex-M4 microcontroller. In the context of the experimental setup presented in the next section, we implemented a comprehensive position control system, complete with a user-configurable proportional gain.

The actuated soft glove is powered by a 3.7 V Li-Po battery which, through a voltage booster, guarantees the 6 V voltage necessary for the motors to rotate at maximum speed. The motors, due to the twisting principle, exert a very limited torque, therefore the needed current is minimal, guaranteeing a battery life compatible with the requirements introduced in Section 2. The MGlove-TS movements can be controlled both via USB and via Bluetooth communication by using the RN-42 Bluetooth module (Roving Networks Inc., US). All the electronic components are placed inside a box and well-protected from accidental contacts and shocks with an external button implemented to power on/off the actuated soft glove and for user safety (see Fig. 1).

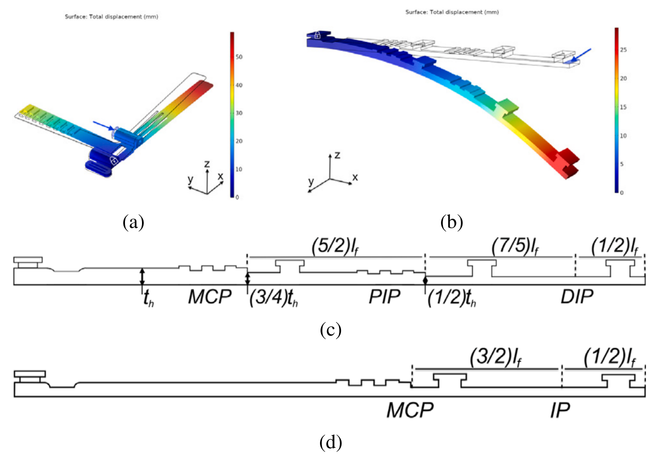


Fig. 5. Compliant structure of the glove supporting tendons. (a), (b)Results of the FEM analysis of the compliant structure of the glove, in terms of deformation. The blue arrow indicates the applied force while the white padlock indicates the fixed parts for the analysis. The applied force has a magnitude of 10 N in (a) and 5 N in (b). (a) simulation of the adduction motion and (b) simulation of the flexion motion. (c), (d) Flexible structures of the glove. The CAD is parametric and can be adapted by varying the thickness t_h and the length of the distal phalanx l_f. (c) Index and (d) thumb elements.

4.1. The glove

The structure of MGlove-TS is soft, manufactured with the Flex-45 thermoplastic co-polyurethane material to ensure the user's comfort and the needed adherence to the user's hand. The support can be adjusted to fit different hand sizes.

The glove consists of one part that wraps around the user's palm and a number varying from 1 to 5 finger modules. In Fig. 4, red circles indicate the parts used to fix the thumb and finger modules, while green circles indicate the elements allowing to close the glove around the palm and to adapt the device to different hand sizes. The cylindrical elements that can be noticed in Fig. 4 are the anchor points in which the tendons are routed. In order to reduce the friction between the tendons and the structure and to increase the user's ergonomics, flexible plastic tubes are used in the anchor points of the palm side. In contrast, small plastic tubes are installed inside all the remaining anchor points.

Each finger module consists of two parts: a set of bands connecting the module to the fingers, containing the anchor points, and a compliant structure, whose design is inspired by [40] controlling finger bending and allowing passive extension motion when the TSA is not actuated. One band per phalanx is needed, so the index module has three bands, while the thumb module has two bands.

The 3D-CAD model of the band is parametric, to adapt the device to the specific user. The parameters defined are the length and the distance between the anchor points. This allows for securing the finger module according to the user's finger dimensions. As introduced in Section 3, the position of the anchor points along the finger is very important for device kinematics. The anchor points, used to route the tendons, are positioned along the middle plane that divides lengthwise the finger, as shown in Fig. 2.

The bands connected to the proximal and intermediate phalanges have the same structure, with different distances between the anchor points. The fingertip band is designed to wrap the fingertip. In this case, the anchor points are longer; one-half of them is rigidly connected to the band, while the other half is not constrained. This allows to solve the tendon pre-tension problems when adduction/abduction movements are performed, i.e. when one tendon is pulled and the other tendon, which remains pre-tensioned, must not hinder the movement of the first one. This behavior has been preliminary verified by means of a stationary structural analysis based on the Finite Element Method

(FEM), on the CAD model of the fingertip band, whose results are shown in Fig. 5(a). The study is performed using COMSOL Multiphysics 6.0 software. The results reported in the figure are in terms of displacement and the applied force magnitude is 10 N.

Each anchor point of the fingertip has a system for manually pre-stretching the tendons, indicated as tendons locking pins in Fig. 4. The tendon-locking pins are made in acrylonitrile butadiene styrene (ABS) and consist of a perforated cap used to pass and fix the tendon to the anchor point.

The second part of the glove is represented by the flexible structure on the back of the finger and the thumb. The structures realized for the index and thumb are shown in Fig. 5(c) and 5(d). This structure is designed to passively extend the finger when the TSAs are not active. Similarly to the grippers described in [40], the structure is a monolithic element with variable bending stiffness. While in [40] the adjustment of the stiffness is realized by varying the parameters of a wave-shaped element, and in [41] by varying the infill density percentage during the manufacturing process, in this paper the stiffness is modified by regulating the cross-sectional thickness along the profile.

Given a stiffness initially fixed at MCP, the stiffness of the other joints is automatically obtained. The ratio between the stiffness values at the PIP and DIP joints is defined to obtain proper coordination of the joints when the tendons are pulled [41]. In this paper, such coordination has been defined according to the [31] ratios and the phalanges lengths ratio derived from [42].

To verify that the structure is suitable for flexion/extension of the human finger, a FEM analysis was performed. The results are reported Fig. 5(b). The force applied to the tip of the compliant structure has a magnitude of 20 N, and is indicated with the blue arrow in Fig. 5(b). The opposite part of the compliant structure, indicated by the white padlock, is constrained and the material used is polyurethane. Polyurethane material was selected for this part of the device because of its elongation and fatigue resistance, which allow repeated movements of the glove finger module. Moreover, it is able to provide a good damping ratio suitable for absorbing shocks [43]. The position of the anchor points and the compliant structure allow us to satisfy the initial requirements and obtain the adduction/abduction and flexion/extension movements. It is worth noticing that this type of compliant structure allows finger bending along only one axis while limiting the other two as reported in Fig. 5(b).

4.2. Actuation unit

MGlove-TS actuation exploits a hybrid solution combining simple and twisted tendons designed to realize both the adduction/abduction and flexion/extension movements with the same structure.

The actuation unit for each finger consists of two modules, each composed of a support, an actuator, and two tendons. The support on one side houses the motor, and on the other side contains the tendons' twisting. The cables used for the prototype (polyethylene Dyneema fiber, Japan) have a diameter of 0.6 mm and each of them can lift up to 450 N.

A bracelet, hosting up to 10 actuators, is used to fix the actuation unit to the user's forearm Fig. 6(a). The modules can be placed around the user's forearm and they can fit together by means of the lateral module hinges. The bracelet is fixed to the user's forearm using strips meanwhile new modules can be added as needed. The 3D-CAD model of a single support is shown in Fig. 6(b). When the glove is used with only two finger modules (such as thumb and index fingers modules or index and middle fingers modules) we have simplified the actuation module support by eliminating the hinges from the design. In this case, two bands, made of thermoplastic material, are used to fix the actuation unit to the user's forearm. Similar to the previous configuration, the modules can be placed anywhere around the user's forearm along the bands. The bracelet presented in this work is a preliminary solution aimed at demonstrating the possibility of hosting up to ten actuation

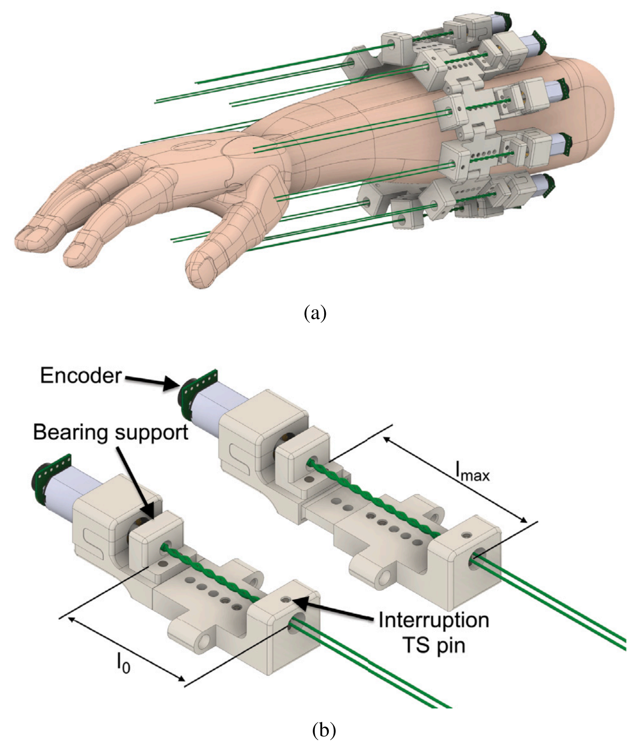


Fig. 6. Actuation units: assembly on the forearm and structure. (a) Actuation unit bracelet. (b) TSA module, composed of a support, a DC motor, and a TS part delimited by an interruption TS pin. TS length is adjustable between l_0 = 41 mm and l_{max} = 53 mm.

units on the forearm. It has a simple structure and can be adapted to users' needs. The main drawback of this solution is that all the forces to actuate the fingers are currently resisted by the friction between the acting unit and the arm and therefore could slide on the skin or have excessive pressure on the arm skin. This problem can be solved by fixing the bracelet on the sleeve of a jacket or shirt made of an inextensible fabric, for instance, cotton, by means of Velcro or other types of connections. In this way, the reaction forces generated by the actuators while pulling the tendons are applied on the sleeve, and the forearm is not stressed. Depending on tendon routing, actuation forces could also interact with wrist articulation motions. To solve this issue, a possible solution consists of wearing a splint that fixes the wrist, with a shape properly defined to provide a uniform pressure distribution to the forearm. Future improvements of this study will focus on the design optimization of actuator positioning on the forearm and tendon routing. To minimize the effort that the DC motor exerts to twist the tendons, a ball bearing with an internal diameter equal to that of the motor shaft is used (Fig. 6(b)).

The twisted string actuators are assembled in two phases: in the first phase, the DC motor is inserted into the support and the two tendons, are passed through the bearing, in the second phase the tendons are fixed to the actuator motor shaft that is then stuck in the bearing.

Due to the conic shape of the human forearm, the force that the TSAs are able to realize could cause sliding of the actuation unit. A pin is inserted at one of the end support parts (interruption TS pin) to confine and control the twisted tendon length: in this way, a hybrid twisted/untwisted tendon transmission is realized. The tendons are routed along palm paths meanwhile the twisted strings, isolated in the actuation module, are in charge of applying the force. As can be seen in Fig. 6(b), the length of the twisted part can be adjusted between l_0 and l_{max}. In the prototype, the TSA module is realized with a resin material, with l_0 = 41 mm and l_{max} = 53 mm.

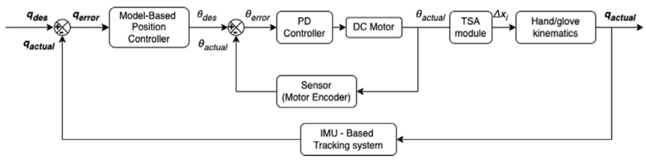
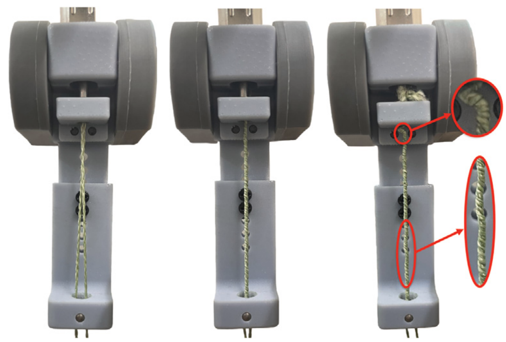


Fig. 7. Control scheme for the MGlove-TS modules.



(a) (b) (c)

Fig. 8. Different possible configurations of the TSA module. (a) Initial position of the TS. (b) Regular twist of the tendons. (c) Tendon over-twisting, irregularities in tendon twisting are highlighted with red circles.

4.3. Device control

In this paper, we focus mainly on glove applications in rehabilitation and control tasks, in which the user is asked to perform pre-defined exercises. Therefore, for this application, the glove can be controlled in position.

A position control has been designed for each TSA module (Fig. 7). The control scheme is defined by two main loops. The external one is managed at the glove level, it takes as input the desired position for the finger or the thumb $\mathbf{q}_{des}$, and compares it with the actual one $\mathbf{q}_{actual}$, measured by an IMU-based tracking system as described in [4,29], the error is elaborated by means of a model-based position controller, developed on the basis on the kinematic relationships for the glove and the TSA previously introduced, which evaluates the corresponding reference values θ_{des} for the TSA motors. Then, a simple PD control is used to control each motor. An encoder sensor is integrated into the TSA actuation unit to measure the string rotation θ_{actual}. This measurement serves as feedback to the control system, providing real-time information about the current state of the string. The PD controller then processes this feedback data.

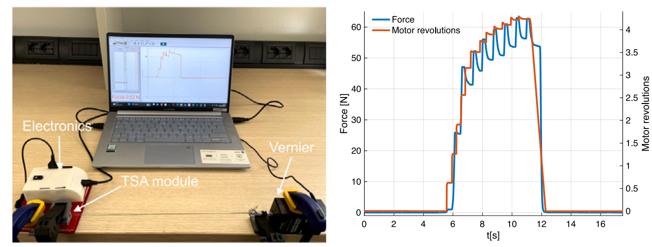
The proportional and derivative gains can be regulated to obtain the desired control performance. The PD control system generates control signals that drive the TSA actuators to achieve the desired finger movements. As a result, the glove wearer can experience precise and coordinated bending and extension of the fingers.

A preliminary calibration procedure is needed to set the parameters of the model-based finger position control, which depends on user-specific data, as discussed in Section 3.

5. Experiments

The experiments carried out to evaluate the prototype of hand soft-glove exoskeleton are divided into three main parts: the first one is for the single TSA module characterization, the second and third ones aim at verifying the proposed glove in terms of forces exerted at the fingertip, abduction/adduction motion, and glove impact on hand-free motions.

Since the glove is designed based on the users' feedback and needs, and on their anthropometric characteristics, only two potential users



(a) (b)

Fig. 9. TSA force evaluation. (a) Experimental setup. (b) Representative trial (with l_{max}).

were involved in the testing phase of the device. The methodology used is the "Single-Case-Design (SDC), which is usually used in the clinical medical field where a single individual is used as a unit of data analysis [44]. Both the users were adult (aged 30 and 27 respectively) and male.

The subjects gave their written informed consent to participate and were able to discontinue participation at any time during experiments. The experimental evaluation protocols followed the declaration of Helsinki, and there was no risk of harmful effects on the subject's health. Data were recorded in conformity with the European General Data Protection Regulation 2016/679, stored locally, and used only for the post-processing evaluation procedure. No sensible data were recorded. One of the subjects has severe limitations in extension and reduced problems in flexion wrist motions and severe limitations in closing/opening the hand. Furthermore, the patient presents low residual force, low active control of the hand and wrist, low spasticity, and low muscle tone. The other subject was involved in testing the soft glove functionality and did not present significant limitations in hand movements and force.

5.1. Experiment 1: Characterization of the TSA module

The characterization of each TSA module was assessed by means of two main tests, i.e. *(a)* evaluation of the TSA maximum force, *(b)* relation between the displacement of the TS and motor revolutions.

As previously described in Section 4.3, the TSA module length can be varied, to make TSA characteristics and in particular the fingertip force adaptable to the user's specific needs. In these two experiments, all four actuation modules that compose the glove actuation unit were tested. For each TSA module, each of its lengths, i.e. starting from the initial length l_0 to the final length l_{max}, was evaluated. Specifically, for the proposed actuated soft glove, the evaluated lengths were 41 mm, 45 mm, 49 mm, and 53 mm. During the tests over-twisting configuration was avoided [37,45], since above this limit, the TSA shows noticeable hysteresis, evident non-linearity, and non-repeatability, which influence glove behavior and performance. Therefore, for all the tests the DC motors were stopped before tendons' over-twisting occurs. For the sake of clarity, in Fig. 8 three different configurations are reported: untwisted tendons, tendons regularly twisted, and over-twisting.

Test 1. The test investigated the TSA module's maximum pulling force. The experimental setup is shown in Fig. 9(a): it consisted of a digital dual-range Vernier dynamometer (Vernier Software & Technology, US) with an accuracy of 0.05 N, horizontally aligned with the module to be tested. Both the dynamometer and the module were rigidly fixed on the table. The dynamometer was connected to the TSA module through a tendon. For each length of the TSA module, the test consisted of making the DC motor perform a step profile, repeat it five times, and record the force exerted. The maximum force for each test was evaluated as the mean of the maximum peak forces between the five trials. The step profile is visually controlled by the tester to avoid the tendons over-twisting. The data were collected with a frequency of 100 Hz and

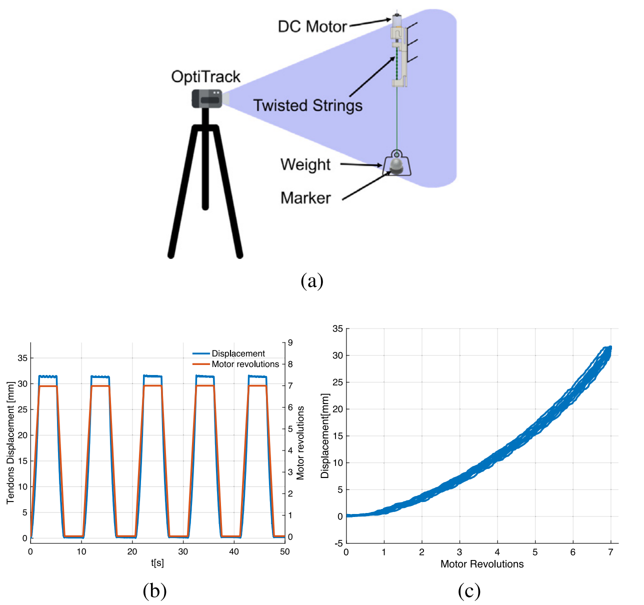


Fig. 10. TSA displacement/motor revolutions characterization. (a) Experimental setup. (b) Representative trial (length l_{max}). (c) Actuator displacement as a function of the number of revolutions, for the same trial.

each trial lasted 30 s. The results obtained for one TSA module with $l = 53$ mm are shown in Fig. 9(b). The oscillatory behavior that can be observed is due to tendon stretching release, which happens each time the motor is kept at a fixed position close to the limit force. It can be noticed the last step has a force lower than the step before because in this phase over-twisting occurs.

The overall results, in terms of maximum mean force among the four TSA modules are 57.33 ± 0.45 N, $53,62 \pm 0.36$ N, 49.83 ± 0.41 N and 47.09 N$\pm$0.56, for length values of 53 mm, 49 mm, 45 mm, and 41 mm, respectively.

Test 2. This test was realized to relate the motor number of revolutions to actuator linear displacement. In Fig. 10(a) a schematic of the experimental setup is shown. It consisted of a motion capture camera system, V120 Trio 6-DoF object tracking (OptiTrack Systems, UK) with a positional accuracy of ± 0.2 mm, fixed to the ground, in front of the TSA module to be evaluated. The TSA module was positioned vertically and a 500 g weight, equipped with a 6.4 mm retro-reflective marker to track the motion, was connected to keep the tendons in tension [36]. The test consisted in controlling the DC motor to rotate a predefined number of revolutions between zero and θ_{max} defined in (11), recording the actual motor shaft number of revolutions and the position of the weight attached to the end of the tendons. Data were collected at a frequency of 100 Hz and each trial lasted 50 s. Fig. 10(b) and Fig. 10(c) show the results for a single TSA module with length l_{max}. The results obtained for each TSA module of the actuation unit are at the basis of TSA position control and are in line with the numerical results shown in Fig. 3(b).

5.2. Experiment 2: Evaluation of the forces at fingertip

To evaluate the force that the actuated soft glove is able to apply at the fingertip, we conducted a test for each size of the TSA module for both the index and the thumb. For these tests, the user with limited hand functionalities was involved. As shown in Fig. 11(a) the setup consisted of a structure that is fixed rigidly on a planar surface, and a high-precision ATI force/torque sensor (ATI Industrial Automation Inc., US). The structure supported the user's hand maintaining the palm parallel to the table surface and easing the contact between the fingertip and the force sensor surface. The force sensor was fixed rigidly on the same table surface and it was capable of measuring forces and moments in the $x - y - z$ directions with an accuracy of 0.04 N and 0.002 Nm, respectively, with a maximum frequency of 7 kHz. For each of the tests, the user's hand wearing the actuated soft glove was inserted in the support and the fingertip was positioned on the force sensor. Once the soft glove motors are activated, the force applied by the fingertip on the force sensor was measured for 30 s at 100 Hz. The user was asked to keep the hand passive and not to resist the force applied by the MGlove-TS.

Table 3
Mean force at the fingertip for each TSA module length.

TSA module lenght	Index [N]	Thumb [N]
41 mm	15.82 ± 1.28	13.77 ± 1.83
45 mm	16.67 ± 1.14	14.94 ± 1.31
49 mm	17.24 ± 0.72	15.84 ± 1.57
53 mm	17.95 ± 1.04	16.62 ± 1.74

The forces were applied through the flexion movement of the finger activated by two TSA modules. The actuated soft glove controls the flexion/extension movement by using the results obtained in SubSection 5.1, *Test 2*.

The force exerted by the fingertip was evaluated as the norm of the three components measured by the force sensor. Fig. 11(b) reports the results of one trial relative to the index finger with the TSA module length $l_{max} = 53$ mm while in Table 3 the summary of the results are summarized in terms of maximum force, evaluated as the mean between the maximum forces of five trials for both the index and the thumb.

5.3. Experiment 3: evaluation of glove impact on hand movements

The objective of the third experiment was to analyze the performance of the actuated soft glove in terms of (i) range of abduction/adduction movements, and (ii) user's hand mobility when the glove is not actuated and the glove wearability.

Test 1. The first test is further divided into two phases. The first one evaluated the movement of the user's thumb and index without the glove by using the fingertip support as shown in Fig. 12(a). The experiment involved the user with reduced hand mobility previously introduced.

In the second phase of the test the actuated soft glove, controlled by the tester, supported the user in performing the abduction/adduction motion, the data were acquired by using the setup shown in Fig. 12(b). For both phases, the hand palm was fixed through the white band. To evaluate abduction/adduction angles for both phases an Xsens Mi-3 (Xsens, NL) Inertial Measurement Unit (IMU) was used, embedding an accelerometer, a gyroscope, and a magnetometer in a single chip.

Each of the two phases consisted of asking the user to perform the abduction/adduction movements twice for each of the five trials per finger, acquiring the data at 100 Hz. In the first phase the user is asked to realize two repetitive adduction/abduction motions with his index finger, completing each repetition in approximately 4 s, in the second one the motion was controlled by the MGlove-TS. The test was realized five times without and five times with the actuated soft glove.

Fig. 12 shows the results obtained in two representative trials with and without the MGlove-TS. The results of this test show that the user's index range of motion passed from $18.25° \pm 1.45°$ to $29.61° \pm 0.42°$. A similar test was realized for the thumb. In this case, the abduction/adduction range of motion passed from $29.14° \pm 2.13°$ without the glove to $42.89° \pm 0.48°$ using the presented soft glove.

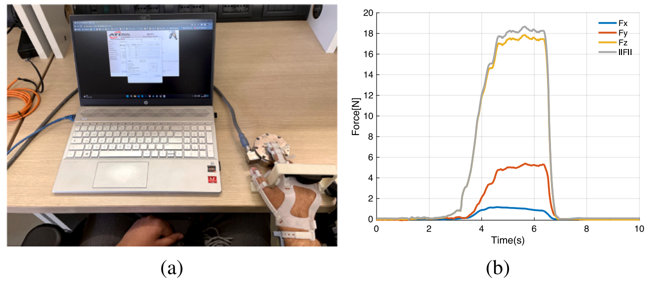


Fig. 11. Evaluation of the fingertip force. (a) Experimental setup. The forces exerted by the glove through the fingertip were measured with an ATI force sensor. (b) Results obtained in a representative trial for the index (module length l_{max}).

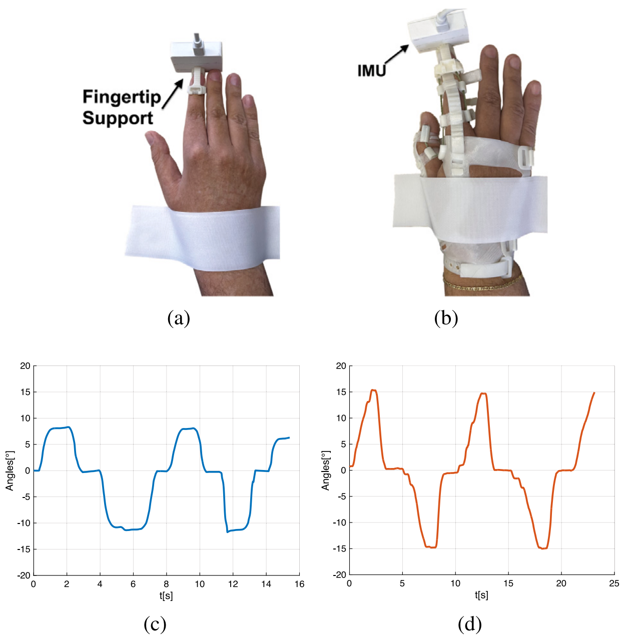


Fig. 12. Index finger abduction/adduction range of motion assessment. (a) Measurement of the free index abduction/adduction motion. (b) Measurement of the same motion controlled by the glove. (c),(d) Results of a representative single trial, (c) without and (d) with the MGlove-TS.

Test 2. The second test aimed to assess the glove encumbrances and hand mobility once the actuated soft glove is worn. To this end, we asked the involved subject to perform the Kapandji test [46] while wearing the exoskeleton. In this case, the test was conducted by the user who does not present noticeable difficulties in moving the hands, with both MGlove-TS prototypes previously introduced, i.e. the partial one, involving the thumb and index finger only (Fig. 13(a)), and the full one (Fig. 13(b)) implementation. In the case of the partial implementation of the MGlove-TS the test consisted of touching four points of the index with the thumb fingertip, i.e. MCP joint, PIP joint, DIP joint, and the index fingertip while wearing the glove without activating the motors. The same points were considered when the user used the full glove implementation. In this case, the test included also touching the middle, ring, pinkie fingertips, and the pinkie MCP joint with the thumb fingertip.

As shown in Fig. 13, the subject was able to touch all the required points. The glove turned out to be comfortable to wear and it does not obstruct the movements of the subject when it is not actuated.

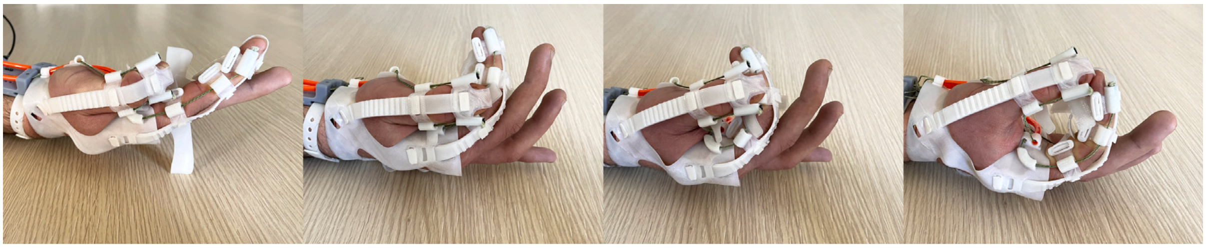
Other tests were performed to further assess the MGlove-TS impact on the activities of daily living. The tests were performed both by the user with limited hand motion capabilities (Fig. 14(a)) wearing the partial MGlove-TS, and by the user without limited motion capabilities (Fig. 14(b)) wearing the full MGlove. It was shown that the glove properly supported the users in grasping tasks of different objects. The results are visible in Fig. 14, for both figures, the images in the first-row show precision or pinch grasps while the ones in the second row show a power grasp posture.

6. Discussion

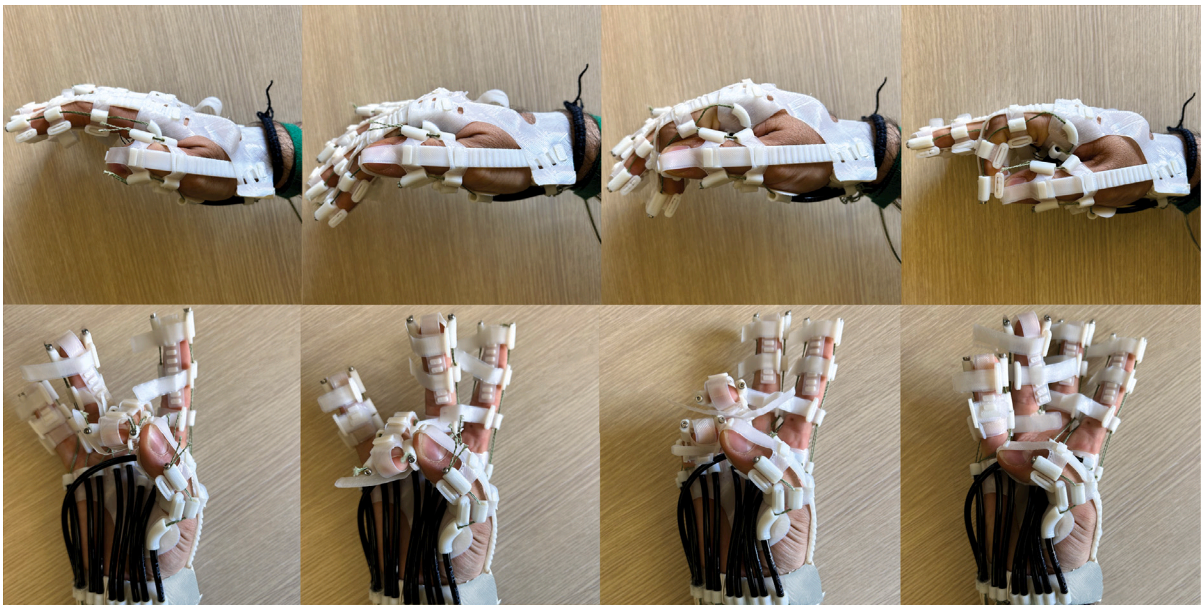
The paper presents the design, development, and preliminary test of MGlove-TS, an actuated soft glove for the hand, based on a flexible structure and twisted string actuation. The results of the preliminary evaluations and experiments show that the glove meets the design requirements both in terms of the range of motion and in terms of force. The single unconstrained actuator is able to apply forces up to 57 N with an actuator length $l = 53$ mm. The corresponding force that can be applied at hand glove fingertips is 18 N. The results obtained from the experiment involving the users confirm that the actuated soft glove is comfortable and does not obstruct the user's movements. Furthermore, it is worth noticing that the soft glove is able to increase the motion amplitude in case of motion limitation. In the experiment, the user abduction/adduction range of motion increased by 11.36° for the index and by 13.75° for the thumb. Such tests also confirm that the abduction/adduction movements are correctly performed by the device. The device has been designed taking into account the problem related to the user's safety and in particular to the DC motor back-drivability. In case of motor failures, blockage, or other types of issues that could block the MGlove-TS in a flexed configuration, the interruption TS pin and the DC motor are easily removable.

To underscore the contribution of our study, we provide a comparative analysis of the Soft Glove developed in this paper with various robotic gloves for hand rehabilitation and assistance that have emerged over the past decade. Table 4 summarizes key parameters, including actuation, transmission, mechanical structure, number of fingers actuated, tip force, system weight, portability, type of motion, modularity, and intrinsic safety. In the following, we provide a short summary of the solutions that we included in the comparison.

Kang et al. [47] designed a glove employing traditional actuation with a gearbox and tendon-pulling mechanism, achieving a fingertip force of 10 N. However, this glove's substantial weight of 1.62 kg limits its portability relative to other solutions. In contrast, Tsabedze et al. [18] developed a glove using twisted string actuation (TSA) which provided 8 N of fingertip force with a small motor. Remarkably, this glove weighed only 0.3 kg, making it highly portable and safe. Nevertheless, it lacked modularity, restricting its adaptability to diverse user needs. Mohammadi et al. [48] utilized a traditional cable-pulling system within their glove, generating 11 N of fingertip force, while maintaining a relatively lightweight design at 0.33 kg, thus achieving a balance between force output and weight. Nycz et al. [49] employed linear actuators and a tendon-pulling mechanism in their glove, resulting in 8.7 N of force. However, the glove's weight was significantly higher (0.8867 kg), making it heavier compared to alternative solutions. Xu et al. [50] developed a glove incorporating a series of elastic actuators (SEA) with links and gears, providing a fingertip force of 10 N, weighing 0.759 kg. Additionally, it featured a semi-soft



(a)



(b)

Fig. 13. From left to right, the different hand positions of the Kapandji test, performed by one of the potential users wearing (a) the partially implemented soft glove and (b) the fully implemented soft glove.

structure. Ryu et al. [51] designed a glove using hydraulic actuators, cable pulleys, and gears. While this system produced substantial force, its weight was 2.740 g, and its portability was challenging. Gloerha Lite et al. [52] represents a commercial glove utilizing a motor, cable, gear, and pulleys, achieving 5 N of fingertip force. However, its weight is around 5 kg, so it is suitable for rehabilitation tasks but is not non-portable. T. Bagneschi et al. [53] developed a glove with a standard cable system, weight information is not available in this case. D. Popov et al. [17] created a glove for the entire hand using a conventional cable-pulling mechanism, producing 16 N of fingertip force. A. Yurkwich et al. [54] incorporated motors with gears, pulleys, and cables to achieve a fingertip force of 2 N, but the design was not modular. Another proposal by A. Yurkwich et al. involved a glove using linear actuators and cables, resulting in a similar fingertip force of 2 N [54].

In the MGlove-TS system presented in this paper, as described in the last row of the table, we implemented a string-twisting mechanism instead of the traditional cable-pulling mechanism. This choice enables our glove to generate a remarkable fingertip force of 18 N using compact motors (3.7 V, 1100 rpm). The device has a lightweight construction, including actuation units, and it is able to perform flexion, extension, abduction, and adduction. The glove has a modular structure so different actuation solutions can be realized. The modular structure of our glove offers several advantages. It facilitates easy customization and adaptation to users' specific needs and requirements. In case of module malfunction or wear and tear, replacing the faulty component is straightforward, eliminating the need for a complete glove replacement. This not only reduces maintenance time but also enhances cost-effectiveness and sustainability, as only the affected module requires replacement. Moreover, the device's modular design allows for future upgrades, further enhancing its usability, cost-effectiveness, and long-term sustainability.

One aspect that has to be considered in a complete assessment of the device is the study of TSA lifecycle, since the strings, subject to continuous and repeated torsion loads, may be damaged. This phenomenon has been assessed in studies available in the literature [55,56]. According to the data available in such works and according to the load and stroke needed in the glove application, we expect that the cables in the TSA employed in the glove could resist up to 15000 flexion/extension movements with the maximum nominal load application. However, a specific study for the assistive glove application will be the focus of future developments of this work.

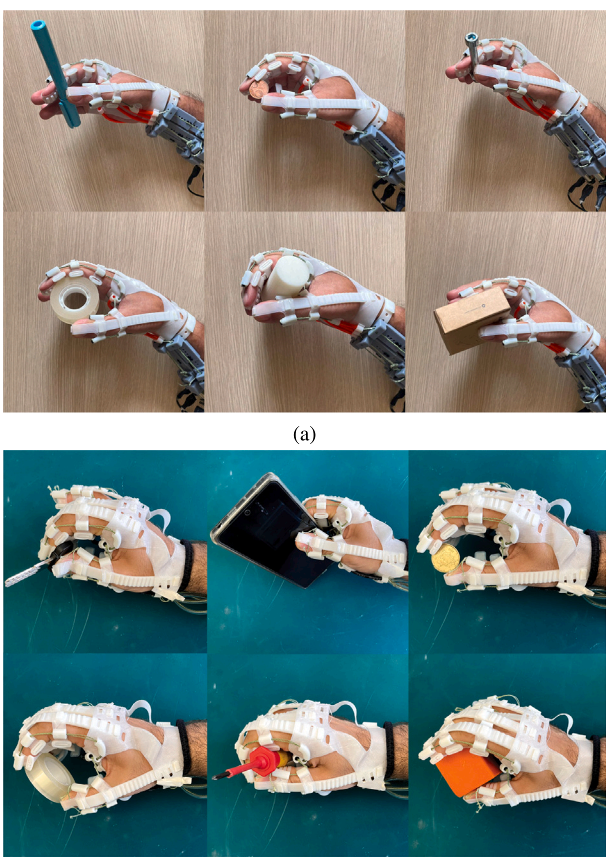
7. Conclusion

In this paper, we presented the main features of an actuated soft glove for rehabilitation, training, and assistance based on a tendon twist actuation system. The device has been developed following a modular approach so that the user can customize it according to his needs. The methodology for creating each finger module is presented. Each finger can be used independently and the "tailor-made" soft glove allows it to be adapted to different hands' characteristics. It is worth highlighting that a user with upper limb impairments and motion limitations was constantly involved in all phases of the project, from the initial design to the prototype development and testing, and, besides participating in the experiments, provided his feedback during the whole design process.

The prototype presented in this paper can be considered currently at TRL 4 (Technology Readiness Level) and is planned to be optimized in the near future. The experimental results obtained in this preliminary phase will be used to enhance the design and performance of the soft glove. Specifically, there is a deviation in the tendon displacements

Table 4
Comparison of recent hand assistive and rehabilitative gloves.

Device	Actuation	Transmission	Mechanical structure	No. of fingers	Tip force (N)	Weight (kg)	Portability	Motion type	Modularity	Intrinsic safety
D. Ryu et al. [51]	hydraulic actuators	links, cable, pulley and gears	semi-soft	3 fingers	12	2.74	No	flexion/extension	No	No
B.B. Kang et al. [47]	Servo motor	2tendon, pulley and gears	soft	3 (thumb and 2 fingers)	10	1.63	No	flexion/extension	No	Yes
C.J. Nycz et al. [49]	linear actuator	tendon, pulley and gears	semi-soft	4 fingers	8.7	0.867	Yes	flexion/extension	No	No
D. Popov et al. [17]	motor	cable, pulley and gears	soft	4 (thumb and 3 fingers)	16	0.34	Yes	flexion/extension	No	Yes
A. Mohammadi et al. [48]	motor	Strings	soft	4 fingers	11	0.33	Yes	flexion/extension	No	No
A. Yurkewich et al. [54]	linear actuator	cable	soft	4 (thumb and 3 fingers)	2	NA	Yes	flexion/extension	No	No
T. Tsabedze et al. [18]	TSAs	strings	soft	5 (thumb and 4 fingers)	8	0.3	Yes	flexion/extension	No	Yes
W. Xu et al. [50]	SEA actuators	links and gears	semi-soft	5 (thumb and 4 fingers)	10	0.759	Yes	flexion/extension	No	Yes
Gloerha Lite et al. [52]	motor	cable, pulley and gears	soft	5 (thumb and 4 fingers)	5	5	No	flexion/extension	No	Yes
T. Bagnesch et al. [53]	servo motor	cable, pulley and gears	soft	3 (thumb and 2 fingers)	10.5	NA	Yes	flexion/extension	No	No
MGlove-TS	TSAs	strings	soft	5 (thumb and 4 fingers)	18	0.15 (2 mod.), 0.375 (5 mod.)	Yes	flexion/extension, abduct./adduct.	Yes	Yes



(a)

(b)

Fig. 14. Completion of some grasp tasks by subjects (a) with reduced mobility using the partial implementation of the MGlove-TS and (b) without reduced mobility using the full MGlove-TS implementation. For both figures, in the first row of the pictures, three pinch tasks are performed, while in the second row, three power grasp tasks are performed.

between the theoretical and the actual motor revolutions caused by the TSA mathematical formulations not considering the pin that restricts the TS (twisted strings) zone. The future development of the device will focus on refining the mathematical model to take into account the variable TS zone of the TSA module and exploring the possibility of using TSA for self-sensing with conductive materials [57]. This capability offers intriguing opportunities in terms of control. Finally, ad-hoc user interfaces and apps for PCs, tablets, and smartphones will be developed to control the device to improve user accessibility and monitor the rehabilitation process, with the possibility of recording and re-playing physical therapist-guided activities.

CRediT authorship contribution statement

M. Dragusanu: Main idea, Conceptualization, Methodology, Software, Data curation, Writing – original draft, Writing – review & editing, Validation. **D. Troisi:** Image elaboration, Writing – original draft, Conceptualization, Validation. **B. Suthar:** Visualization, Investigation, Writing – original draft, Writing – review & editing, Conceptualization, Methodology. **I. Hussain:** Visualization, Conceptualization. **D. Prattichizzo:** Supervisor, Visualization, Conceptualization. **M. Malvezzi:** Supervisor, Conceptualization, Visualization, Methodology, Writing – original draft, Writing – review & editing.

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

Data will be made available on request.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.mechatronics.2024.103141.

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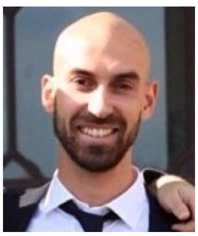

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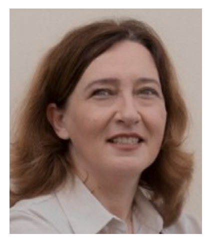

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