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Fully Wearable Actuated Soft Exoskeleton for Grasping Assistance in Everyday Activities

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Abstract

Worldwide, over 50 million people suffer from persistent hand impairments after stroke or spinal cord injury (SCI). This results in major loss of independence and quality of life. Robotic hand exoskeletons can compensate for lost motor function and assist in grasping tasks performed in everyday activities. Several recent prototypes can partially provide this assistance. However, it remains challenging to integrate the dexterity required for daily tasks in a safe and user-friendly design that is acceptable for daily use in subjects with neuromotor hand impairments. We present the design of RELab tenoexo; a fully wearable assistive soft hand exoskeleton for daily activities. We present sleek mechanisms for a hand module that generates the four most frequently used grasp types, employing a remote actuation system that reduces weight on the hand. For optimal assistance and highest adaptability, we present various design and control options to customize the modular device, along with an automated tailoring algorithm that allows automatically generated hand modules for individual users. Mechanical evaluation shows that RELab tenoexo covers the range of motion and the fingertip forces required to assist users in up to 80% of all grasping activities. In user tests, we find that the low weight, unintrusive size, high wearing comfort, and appealing appearance are beneficial for user acceptance and usability in daily life. Finally, we demonstrate that RELab tenoexo leads to an immediate improvement of the functional grasping ability in a subject with SCI.

Keywords: wearable robot, hand exoskeleton, compliant structure, assistive technology, soft robot

Introduction

Due to stroke[1,2] and spinal cord injury (SCI),[3] ~50–60 million people live with neuromotor hand impairments worldwide. Consequently, they suffer from a major loss of independence and quality of life. Despite undergoing the typical treatments to restore hand function such as orthopedic surgery, medication, or physical and occupational therapy, the recovery of these subjects' plateau, and the residual ability of the hand are not expected to improve further. Such subjects therefore learn to complete daily tasks with their remaining abilities and through compensatory strategies.[4] In addition, assistive equipment such as eating utensils, key turners, and writing devices are used to increase safety and independence in activities of daily living (ADL).[5,6]

Wearable robotic hand exoskeletons can improve the independence of the users by improving performance on functional grasping tasks. In the past decade alone, over 140 hand exoskeletons have been developed, 48 of which were intended to assist in daily life.[7] However, very few devices are commercially available (e.g., neomano; Neofect, Korea; carbonhand; Bioservo, Sweden) and none is covered by social insurance. To achieve better overall usability, hand exoskeletons for assistance in daily life have to fulfill various requirements regarding functionality, efficiency, and user satisfaction.[8] In particular, they need to be able to assist various functional grasp types and generate sufficient assistive force. At the same time, in contrast to stationary rehabilitation devices (e.g., Gloreha; Idrogenet srl, Italy; Hand of Hope; Rehab-Robotics, China), they need to be lightweight and small. In addition, they must be ergonomic, comfortable, and visually appealing to the user.

State-of-the-art assistive hand exoskeletons mostly use rigid link structures or tendon-based mechanisms. Rigid link structures generate finger-flexion-like motions through kinematic chains with the mechanism alone (no human finger in the mechanism).[9] This is beneficial for safe interaction because forces, and particularly the force directions, can be controlled accurately. Generally, rigid link structures are

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mounted on the dorsal side of the hand and apply forces perpendicular to the flexion/extension plane of individual phalanges, or the fingertip. Rigid link structures, by nature, have limited compliance and large form factors. Especially, when thumb opposition is assisted, the form factor and weight of such structures rapidly increase due to the complex motion patterns that are required.

Soft, tendon-based mechanisms guide wires (tendons) along the dorsal and the palmar side of the fingers.[10] Pulling on either of the tendons generates flexion/extension, similar to physiological finger flexion/extension. Such mechanisms are inherently lightweight and have a low profile. However, the applied forces, and especially the force directions, cannot be controlled accurately, thus resulting in a potential risk for the user.

Hand exoskeletons with soft pneumatic actuators can exert well-directed forces and are naturally more compliant and lightweight than rigid structures. However, most available devices consist of bulky hand modules and require a remote air pressure supply.[11–13] This highlights a need for novel solutions that combine the advantages of rigid link structures and soft mechanisms, and that provide a good trade-off between functionality and factors affecting usability in daily life.

In this article, we present the fully wearable, actuated soft hand exoskeleton RELab tenoexo, which combines features of rigid link structures and soft mechanisms, and allows natural grasp adaptation in an extremely lightweight and sleek design. We describe the design process that enabled us to improve the usability of the exoskeleton for people with hand impairments. In particular, we identify detailed requirements for assistive hand exoskeletons and present a design that reduces the dexterity of the human hand to only three degrees of freedom (DOF). This is sufficient to generate the four most frequently used grasp types[14] and cover up to 80% of daily grasping activities.

With a strong focus on usability in daily life, we present various options for customizing the modular exoskeleton to the needs of individual users. To optimally adapt the device to specific hand sizes and user needs, we present an automated tailoring algorithm, which allows automatically generated new hand modules based on hand anthropometrics, kinematic relationships, and desired wrist angles. We evaluate the functionality of RELab tenoexo in terms of grasp types, fingertip force, range of motion (ROM), weight, and size. In user tests, we evaluate the usability in daily life, including comfort, appearance, and perceived weight, and investigate the immediate effect on the functional ability of subjects with neuromotor hand impairments. Finally, we compare the features of RELab tenoexo to related work and highlight its advantages and limitations.

Design

Design case and requirements

The functional abilities needed to perform basic ADL are similar for everyone. However, the type and level of required assistance vary considerably with presence of spasticity, contractures, muscle tone, and joint stiffness in the hand, not only in subjects with different neuromotor diseases (e.g., SCI, stroke, and brachial plexus injury)[8] but also in subjects with the same disease.[15] Therefore, rather than focusing on a target population based on diagnosis, we designed RELab tenoexo as an assistive device for use in daily living for any individual with severely affected hand motor function, low residual force, and low active control of the hand. Potential users should have sufficient proximal control to position the hand, low spasticity, and low muscle tone.

We derived detailed requirements for this design case from the literature, interviews, and usability tests with previous prototypes in subjects with neuromotor hand impairments. For a better overview, we organized the requirements in two groups that typically create a difficult trade-off for assistive technology; functionality and usability in daily life (Table 1).

The functionality is composed of

- Functional grasp types
  For which Vergara *et al.*[14] and Bullock *et al.*[16] found that four grasp types (palmar pinch, medium wrap, parallel extension, and lateral pinch [denomination of Feix *et al.*[17]]) and a flat hand, not actually grasping the object, can account for over 80% of all grasping activities executed in daily living. To execute these most frequently used grasp types, the thumb needs to be able to abduct and adduct, and to be used in pad opposition (e.g., precision pinch) or side opposition (e.g., lateral pinch).[14,17]
- Functional ROM
  Including flexion/extension and abduction/adduction of the fingers, flexion/extension and abduction/adduction in combination with internal/external rotation of the thumb, as well as flexion/extension and radial/ulnar deviation of the wrist.[18,19]
- Grasp force
  Sufficient to lift objects weighing up to 1 kg, for example, to drink from (specifically mentioned 750 mL) water bottles independently.[8] The necessary fingertip force is $F_{\text{Fingertip}} = \frac{m \cdot g}{4 \cdot \mu} = 10\,\text{N}$, with $\mu = 0.25$.[11,20] This value is in accordance with values from further literature (Table 1).

The most important points we identified for the usability in daily life include the following:

- Low weight and small form factor
  Below the suggested maximal weight of assistive hand exoskeletons, which mostly ranges between 300 and 500 g.[7,21,22] Subjects with hand impairments suggested that a weight of 200 g on the hand was "manageable."[8] Anything larger than 5 cm × 5 cm × 3 cm on the back of the hand was "too bulky."[8]
- Fast, independent donning and doffing of the device
  Preferably, a quick (few seconds) out of the box solution.[8] However, we also found that fast donning with the help of an untrained person or self donning below ~2 min (e.g., before lunch) is acceptable.
- Continuous use for the whole day[8]
  Which can be approximated by 600–700 grasping motions per hour (opening and closing cycles) and 5 h of continuous use.[14,16]
- Safe user interaction
  At any time, especially considering that some individuals with impaired hand function may have limited functional or passive ROM due to muscle stiffness or contractures.[8,15]
- 1–2 s duration of the hand closing movement[8]
- Water resistance and cleanability.
- Intuitive, reliable control[23,24]
- Unrestricted ROM of the arm.

Table 1. Requirements for a Fully Wearable Assistive Hand Exoskeleton, Separated into Functionality and Usability in Daily Life. In addition, the Percentage of Activities of Daily Living That Can Be Executed, If the Requirement Is Met, and the Corresponding References Are Listed

	Requirement	*Values*	*% ADL covered*	*Reference*
Functionality	Grasp types	Palmar pinch, medium wrap, parallel extension, and lateral pinch	80	14,16
	Finger flexion	MCP 70°, PIP 80°, DIP 60°	100	41,42
	Thumb flexion	MCP 30°, IP 40°	100	41
	Thumb abduction/adduction	MCP –6° to 21°, CMC –8° to 16°	100	18
	Thumb external rotation	28°	100	18
	Wrist flexion/extension	–40° to 40°	70	19
	Wrist radial to ulnar deviation	–10° to 30°	70	19
	Fingertip force	10 N	75–100	56–58
Usability in daily life	Weight	200 g		8,48
	Volume	$5 \times 5 \times 3\,cm^3$		8
	Intuitive control	90% accuracy, max. 300 ms delay		23,24
	Duration of closing movement	1 s		8
	Battery runtime	5 h with 600–700 grasp cycles p.h.		8,14
	Further factors	Comfortable, ergonomic, and appealing design, low noise, unrestricted ROM of the arm		

ADL, activities of daily living; CMC joint, carpometacarpal joint; DIP, distal IP; IP joint, interphalangeal joint; MCP joint, metacarpophalangeal joint; PIP, proximal IP; ROM, range of motion.

Design concept and overview

Devices that fulfill the above functional requirements can help restore the function to complete ~70% to 80% of all grasping activities in daily life with no need for compensatory movements or additional assistive equipment. However, it is very likely that a highly functional device will be bulky, heavy, and cumbersome to use. For RELab tenoexo, we took various decisions to optimize the trade-off between the functionality and the usability in daily life. With the proposed concept, only two motors and a manual slider can generate high functionality covering the four most frequently used grasp types in a lightweight and sleek hand exoskeleton.

- A soft compliant finger mechanism passively mimics the natural flexion sequence from proximal (metacarpophalangeal [MCP]) to distal (proximal and distal interphalangeal [PIP/DIP]) joints[25] upon contact with objects (Figs. 1 and 2).
- Combined actuation of digits 2–5 (flexion/extension and simultaneous ab/adduction) allows a single motor to move these digits according to the first principle component, accounting for over 60% of the variance in hand postures.[26]
- Separate actuation of the thumb flexion/extension and manual positioning of the thumb in different abduction/adduction and rotation angles allow for grasp types with pad and side opposition.
- Fixation of the wrist in a functional (slightly extended) position reduces weight and complexity, but maintains high functionality according to Montagnani *et al.*[27]
- Remote actuation with compliant transmission removes weight from the hand to the trunk and reduces the overall perceived weight.[8,28]
- A modular and tailorable design with various interfaces for fixation and control allows a maximal variety of users to be optimally assisted by RELab tenoexo.

The final design of RELab tenoexo is shown in Figure 3. It consists of a hand module that is attached to the hand and a backpack containing the electronics, motors, and battery. Backpack and hand module are connected through a Bowden-cable-based force transmission system and can be connected through a clip-on mechanism. In the hand module, three DOF enable power, precision, and lateral grasps: combined actuated flexion/extension of digits 2–5, individual actuated flexion/extension of the thumb, and manual side and pad opposition of the thumb. The two DC motors are controlled through force feed forward and actuate the flexion/extension of the fingers and the thumb, respectively, through a rack-and-pinion mechanism.[29] To switch between opening and closing of the hand exoskeleton, either any kind of transistor-transistor logic (TTL) trigger with standard audio jacks or the Myo armband (wireless surface electromyographic [EMG] sensor; Thalmic Labs, Kitchener, Canada) can be used.

Finger mechanism and arrangement in the hand module

The flexion/extension of the fingers and thumb is the key mechanism for grasping gestures and producing the required fingertip force. For RELab tenoexo, we adapted the three-layered sliding spring mechanism presented in Arata *et al.*[30] (Fig. 1a). An actively sliding spring blade is mounted on top of a fixed spring blade. By moving the actively sliding spring through a linear motion in the most proximal segment, the relative length of the springs changes, which results in bending of the springs. With rigid elements connecting the

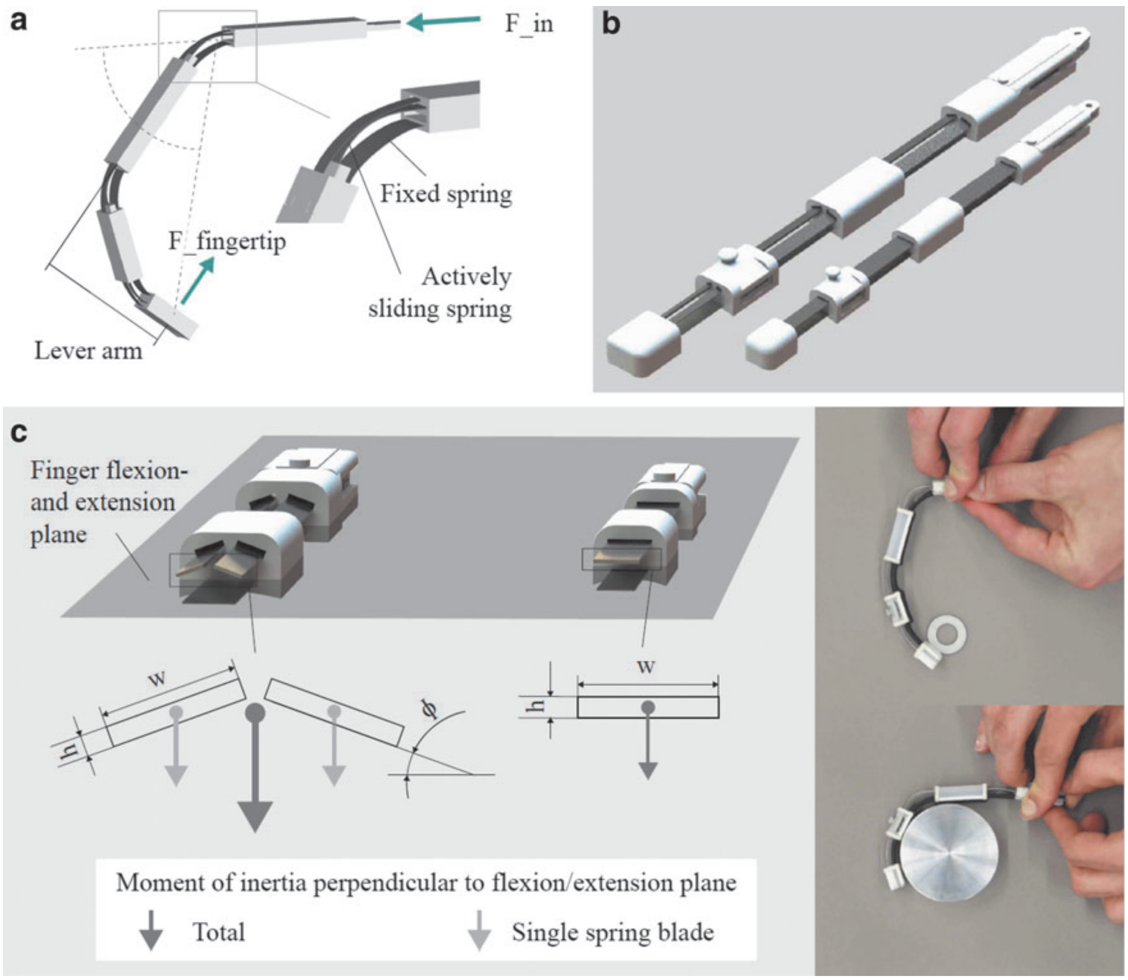


FIG. 1. **(a)** Three-layered spring mechanism, reprinted and adapted from Arata *et al.*[30] When generating force at the fingertip ($F_{fingertip}$), the required input force (F_{in}), torque, and spring stiffness in the joints increase with the finger length (increasing lever arm). **(b)** Two designs of the thee-layered sliding spring mechanism with one (original design) and two actively sliding springs (v-shape design), respectively. **(c)** *Left*: qualitative comparison between the stiffness of the finger (moment of inertia in the finger flexion/extension plane) between the original design and the v-shape design. With the v-shape design, higher stiffness and higher fingertip forces can be achieved. *Right*: default finger motion of the v-shape design, which follows the first postural synergy with high flexion angles in the MCP joint (*top*) and adapts to the shape of an object through the flexion sequence from proximal to distal joints (*bottom*). MCP, metacarpophalangeal.

two springs, the bending can be localized in three segments along the springs, resulting in the final motion that mimics flexion/extension of a human finger. The original three-layered spring mechanism generates fingertip forces of up to 3 N,[30] which is largely below the required 10 N for ADL.

To generate the desired higher fingertip force with the three-layered sliding spring mechanism, we developed a new v-shape design with two angled sliding springs (Fig. 1b). In the three-layered sliding spring mechanism, for a certain fingertip force, the required torque in the joints increases with the finger length (longer lever arm, Fig. 1a). Higher torque can be achieved by increasing the spring stiffness, that is, the moment of inertia I_y of the rectangular profile of the springs:

$$I_y = \frac{w * h^3}{12} \tag{1}$$

where h height of the spring blade
w width of the spring blade.

I_y can be increased by increasing h or w. With the v-shape arrangement, the width and height of the actively sliding spring blades are rotated by an angle ϕ, such that the moment of inertia in the plane of the spring blade I_y remains unchanged, but the moment of inertia perpendicular to the finger flexion/extension plane I'_y increases (Fig. 1c):

$$I'_y = \cos(\phi)^2 * \frac{w * h^3}{12} + \sin(\phi)^2 * \frac{w^3 * h}{12} \tag{2}$$

The width ($w = 1.6$–3.3 mm), the height ($h = 0.2$ mm), and the angle ($\phi = 20°$) of the spring blades were adjusted empirically for each joint until a flexion sequence from proximal (MCP) to distal (IP) joints according to Braido P *et al.* was observed (Fig. 1c). We used cold rolled stainless steel strip (Sandvik 11R51, tensile strength 2050 ± 100 MPa; Precisinox SRL, Italy) for the spring blades, and 3D-printed rigid elements (printed with IP 600 material; Igus, Switzerland).

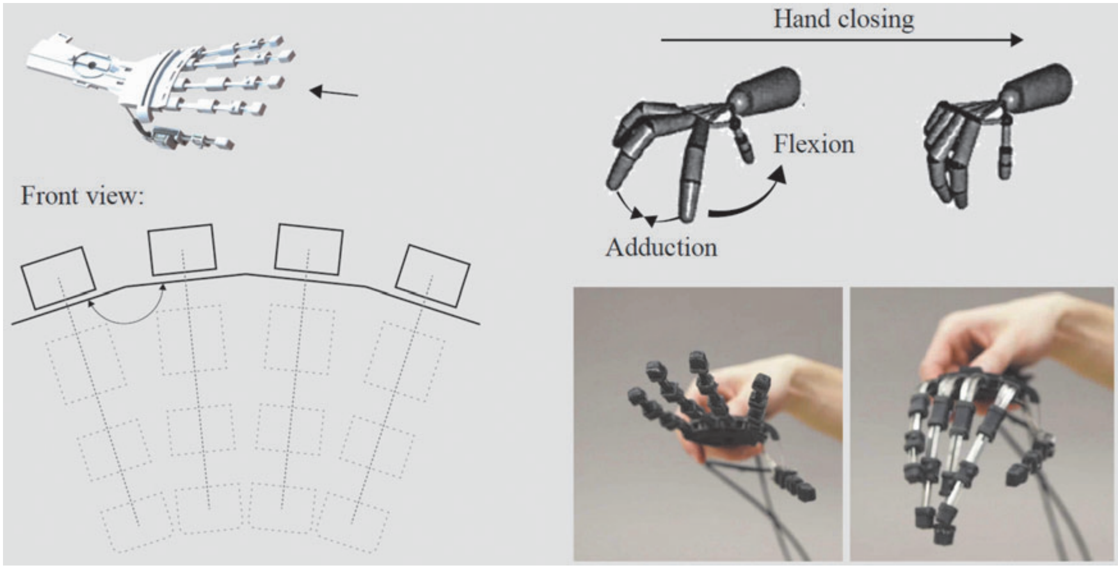


FIG. 2. The fingers are mounted with an angle between the flexion/extension planes of each digit (*left*). This leads to simultaneous flexion and adduction, following the first postural synergy reprinted from Santello *et al.*[26] (*right*).

FIG. 3. RELab tenoexo consists of a hand module with two actuated degrees of freedom and passive thumb opposition, as well as a backpack (motors, electronics, and battery) connected to the hand module through a cable transmission system.[29] Backpack and hand module can be connected through a clip-on mechanism.

In the main body of the hand module, the exoskeleton fingers for digits 2–5 are mounted such that they are free to move in lateral direction and therefore allow for passive abduction/adduction. The four exoskeleton fingers for digits 2–5 are connected mechanically, such that they can be actuated together. By mounting them with a small angle of 10° to 15° in the frontal plane between each other, flexion of the fingers leads to a simultaneous adduction, according to the targeted first postural synergy (Fig. 2).

Thumb mechanism

The thumb motion is divided into actuated flexion/extension and manual abduction/adduction (opposition). The flexion/extension is generated with the same three-layered sliding spring mechanism as for digits 2–5. For pad opposition, the thumb needs to reach large abduction/adduction angles in the carpometacarpal (CMC) joint (Fig. 4). Consequently, the rack used to provide the linear input stroke needs to rotate around the CMC together with the thumb. Therefore, we mounted the rack directly on the thumb between the CMC joint and the MCP joint (Fig. 4).

To flex the CMC joint, the cable-driven pinion rotates and pushes the rack out of a carriage. When the CMC joint is fully flexed, the rack is mechanically blocked. At this point, with further rotation of the pinion, the carriage starts moving. As the carriage is directly coupled with the sliding spring, this motion leads to flexion of the MCP and IP joints. With this compact setup, the thumb shows a flexion sequence from proximal to distal joints.

Four key components work together for thumb abduction/adduction and opposition (Fig. 5): (1) a manual slider and a sliding spring blade (opposition spring) that can rotate in the flexion/extension plane of the thumb around the point where the thumb and the opposition spring are connected, (2) a mechanical stop that, at a certain abduction angle, prevents free rotation of the opposition spring, (3) a ball joint located at the CMC joint that allows for rotation around all axes, and (4) a spring blade that connects the rack and the ball joint.

When the thumb is in adducted position, the opposition spring is almost fully inside the hand module (situation I, Fig. 5). When the slider is pushed, the opposition spring moves out of the hand module and the thumb moves into abducted position (situation II). When the mechanical stop is reached, the rotation of the opposition spring and the rotation around the CMC joint in the flexion/extension plane are blocked. When the slider is pushed further, the opposition spring buckles, which generates a rotation of the flexion/extension plane (situation III). Together with the thumb flexion/extension mechanism, the thumb can generate pad and side opposition.

Hand fixation and remote actuation

The main body of the hand module was rapid prototyped with a stand-alone 3D printer (uPrint SE plus; alphacam, Switzerland). According to Burssens *et al.*[31] and, O'Driscoll *et al.*[32] and after testing various setups for comfort in usability studies, we chose 30° flexion and 5° ulnar deviation for a functional wrist position and applied these angles between the wrist part and the metacarpal part of the hand module.

Three types of fixations to the hand and fingers can be chosen according to the user's preference (Fig. 6a). The first approach, with straps for each finger and the wrist, leaves the palm mostly uncovered and allows for sensory feedback when grasping objects. Importantly, the strap in the palm is placed parallel to the abductor pollicis brevis muscle, such

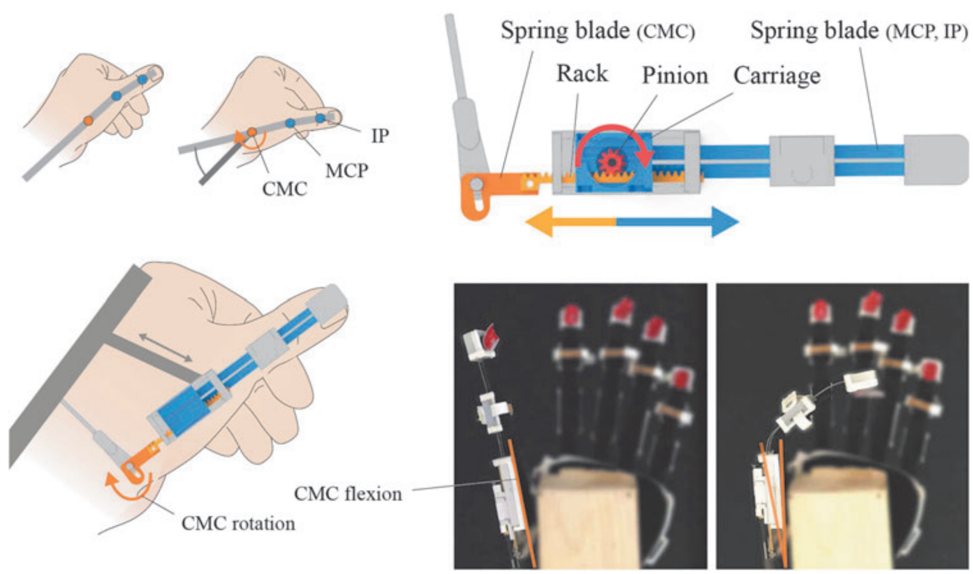


FIG. 4. *Left*: the large variable abduction/adduction (rotation in the CMC joint, indicated in *orange*) leads to misalignment between the thumb and the dorsal side of the hand. The rack and pinion is therefore mounted between the CMC and MCP joints and allows the thumb to rotate in the CMC joint. *Right*: thumb mechanism that acts in two directions. Upon rotation of the pinion, the rack (*yellow*) moves out of the carriage (*blue*) and generates flexion in the CMC through deformation of the spring blade (*orange*). Whenever the resistance in the CMC joint is higher than in the MCP and IP joints (e.g., upon contact with an object in the area of the CMC joint), further rotation of the pinion leads to a displacement of the carriage, which generates flexion/extension of the MCP and IP joints. CMC, carpometacarpal; IP, interphalangeal.

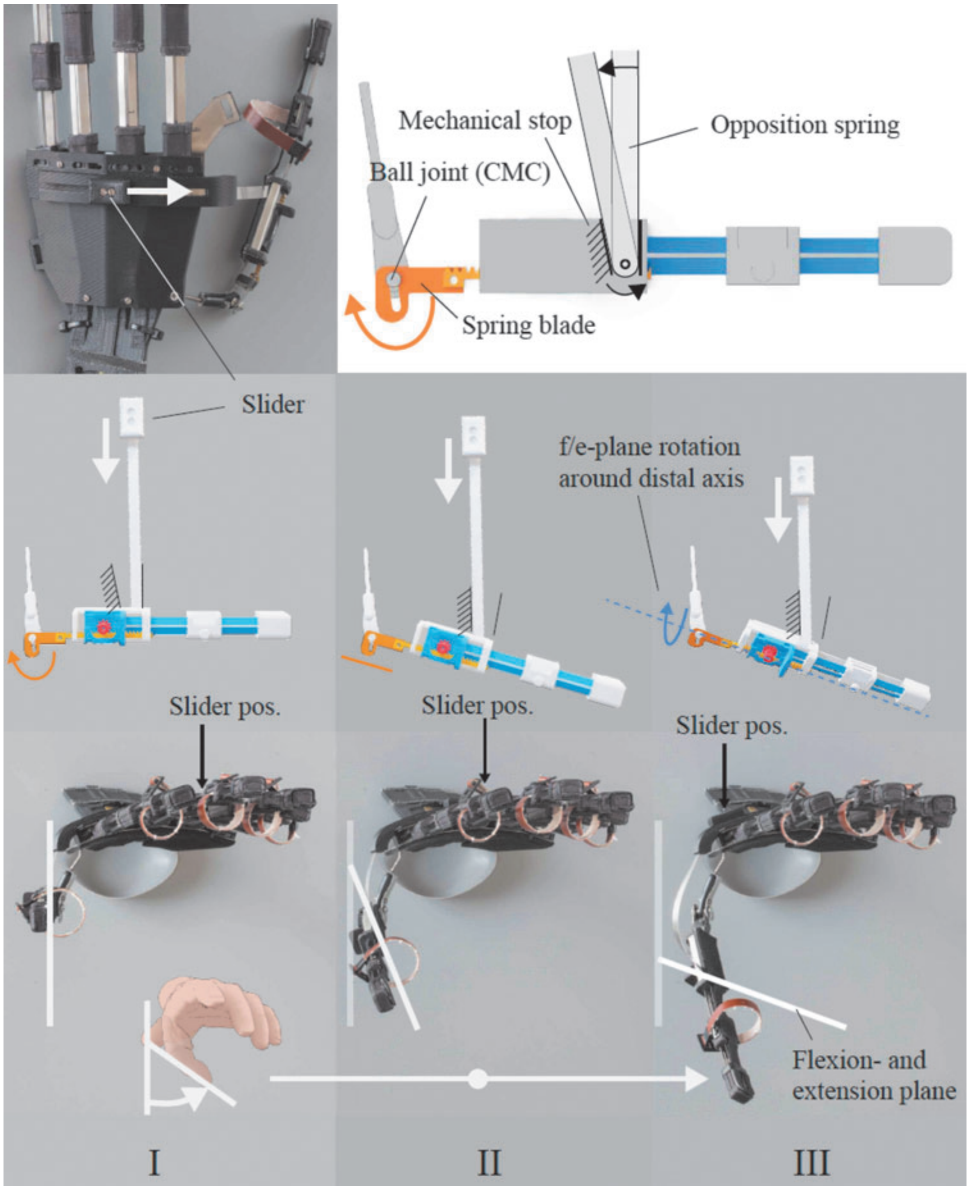


FIG. 5. Thumb adduction/abduction, and opposition mechanism. *Top*: components. *Bottom*: working principle. The thumb is fully adducted when the slider is inside the hand module (situation I). When the slider is pushed, the opposition spring moves out of the hand module and the thumb moves into abducted position (situation II). When the mechanical stop is reached, the rotation of the opposition spring in the flexion/extension plane is blocked. When the slider is pushed further, the opposition spring buckles, which generates a rotation of the flexion/extension around the distal axis of the thumb (*blue dashed line*, situation III).

that as little pressure as possible is applied on the intrinsic hand muscles. The second approach uses a Velcro-covered glove that facilitates donning, but covers the palm entirely. The third way is Velcro-covered fingerlings for fingers and thumb, which cover the fingers, leave the metacarpus free, and further facilitate donning compared to the glove. Together with the normally open (extended) fingers, this setup ensures comfortable and functional default hand position.

We adapted a Bowden-cable-based force transmission system[29] to remotely actuate the hand module. The remote actuation system (RAS) consists of two winches, connected by two ropes which are wound in opposite directions and guided through Bowden cables. The overall bending angle of the Bowden cables is measured with a bending angle sensor.[29] For the final design of RELab tenoexo, we used DC motors with direct torque control and steel wires as ropes, which inherently are elastic and can be tensioned. These changes allowed the omission of the series elastic elements that were previously used to tense the cables and control the force.

Both actuated DOF (thumb flexion/extension and finger flexion/extension) are driven with identical RAS from actuation unit to hand module. Only the diameters of the output winches (24 mm for the fingers and 8 mm for the thumb) and the shape of their housings were adapted to the force and size requirements (Fig. 7b). The wrist and thumb winch can be connected to the hand module with a clip-on mechanism.

Electronics

The main body of the actuation unit contains DC motors (DCX22S with planetary gear GPX22; Maxon Motor, Switzerland), motor controllers (ESCON 24/2; Maxon Motor), a microprocessor for embedded solutions (Arduino Yun Mini, Arduino, Italy), and the bending angle sensor (Fig. 7c). The microprocessor includes a WiFi and a USB-A slot (USB shield, Doghunter) for external communication with a smartphone and the Myo armband. A custom-made printed circuit board connects the motor controllers and

FIG. 6. RELab tenoexo is highly tailorable. **(a)** Three fixation methods: straps for each finger and the wrist, Velcro-covered fingerlings and Velcro-covered glove. **(b)** Three hand modules tailored for three individuals, actuation box that can be used to actuate all three hand modules, and two harnesses of different size. **(c)** Actuation box mounted on a wheelchair. The hand module is stored in a pocket.

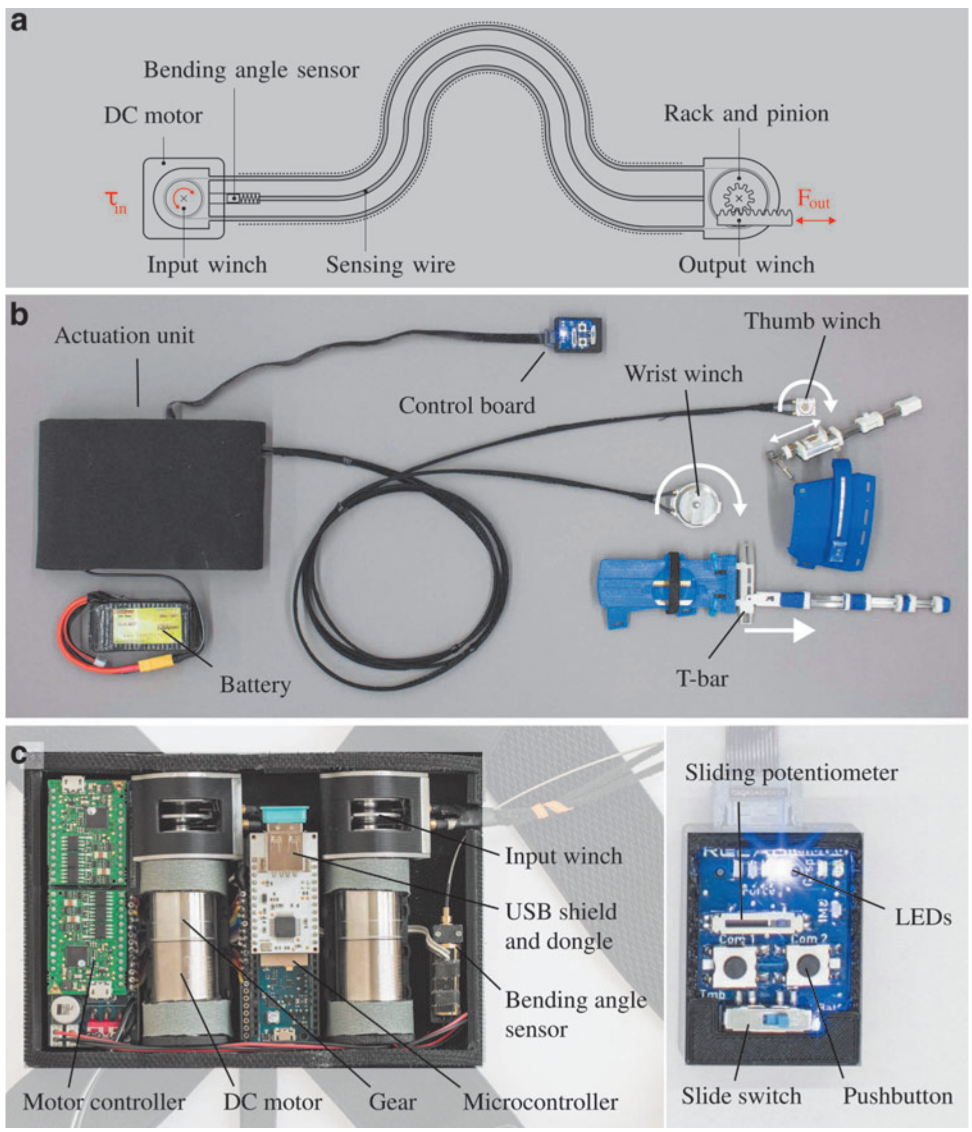


FIG. 7. **(a)** Schematic of the remote actuation system (RAS) adapted from Hofmann *et al.*[29] Upon rotation of the motors, the input winch winds up the rope and rotates the output winch. A rack-and-pinion mechanism generates the linear motion required for finger and thumb flexion/extension. **(b)** Implementation of the RAS for RELab tenoexo, including the power flow from the battery to flexion of the fingers and thumb. The wrist winch moves the T-bar (connected to all fingers) and the thumb winch moves the carriage through rack-and-pinion mechanism. **(c)** Electronic components of the actuation unit and the control board. Pushbuttons, slide switch, and potentiometer are used as user interface and trigger different actions depending on the control mode.

microprocessor and carries the required power electronics as well as two standard audio jacks, which can be used to connect TTL triggers with the audio jack interface (e.g., large-diameter push buttons [Ablenet, Switzerland], EMG sensors, and EEG sensors).

The battery is located in a separate compartment, such that various sizes/capacities can be used. A custom-made control board serves as a user interface and consists of several status LEDs for feedback, as well as a sliding potentiometer, two push buttons, and a slide switch to control the hand exoskeleton. All components are equipped with Velcro so that they can be mounted separately on harnesses of different sizes (Fig. 6b), placed on a desk, or integrated into a wheelchair (Fig. 6c).

Control

The compliant mechanism and intrinsic adaptation to the object to be grasped allow RELab tenoexo to be controlled with the finger input force as a single control parameter. The required motor torque is calculated based on the desired force (e.g., set from the control board), the overall bending angle of the Bowden cables, and the dynamic feed-forward-friction compensation model used in Hofmann *et al.*[29] The motor controller sets the corresponding motor current in a feed-forward control manner. In the transition between two force levels, the controller follows a minimal jerk profile, which mimics a natural biomechanical motion. This setup (bending angle sensor and feed-forward force control) allows operation of RELab tenoexo without the need for sensors in the hand module.

The user should be able to open and close the hand exoskeleton, that is, flex/extend the fingers and the thumb independently. RELab tenoexo provides several control modes based on the two TTL triggers, which can be engaged by the audio jacks located in the actuation unit or the push buttons on the control board.

In the basic control mode, two predefined states (flexed/extended) can be selected by the user. The desired force levels for flexing and extending can be adjusted manually by the sliding potentiometer located on the control board. The triggers are used to switch between opening and closing of the hand exoskeleton. By default, the fingers and the thumb flex and extend simultaneously upon the command from the triggers (''full hand grasp'' for power and precision grasps). To perform lateral grasps, the slide switch on the control board can be activated. In this mode (''thumb only grasp''), the fingers are flexed by default and only the thumb flexes and extends upon the command from the trigger.

In a second control mode, the degree of finger and thumb flexion can be selected continuously. When one trigger is active (i.e., a button is pressed), the hand exoskeleton keeps closing and increasing the force until the trigger is no longer active (i.e., button released), or the selected maximal force is reached. The second trigger is used to open the hand exoskeleton in the same manner. Similar to the first method, the slider is used to set the maximal force and the slide switch is used to toggle between ''full hand grasp'' and ''thumb only grasp.''

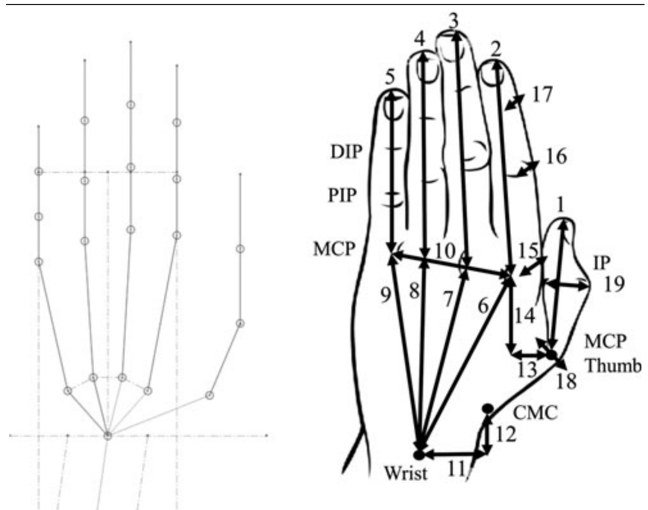
A third control method was developed for users with bilateral paresis, who are unable to use the slide switch and sliding potentiometer on the control board. In this mode, one trigger is used to enter a menu in which sequentially different LEDs light up. The same trigger is used to select higher or lower forces (replacing the sliding potentiometer) or between ''full hand grasp'' and ''thumb only grasp'' (replacing the slide switch). When the menu is activated, an LED lights up for a given amount of time for each option. When the trigger is pressed, while the LED is on, the corresponding option will be selected and the menu will end. The second trigger can be used to close the hand when it is open and conversely.

Finally, RELab tenoexo can be controlled with the Myo armband, based on previous work.[33] After donning the armband, a smartphone application is used to start and guide the user through a short (30 s) classifier training routine. During classifier training, the myoelectric activity for hand opening, hand closing, and resting is recorded. Upon completion of the routine, RELab tenoexo can be controlled by attempting to open and close the hand.

Automated tailoring algorithm

The compliant finger mechanism allows for some variation in terms of hand size. However, to optimally support the user, the hand module should be tailored exactly to the user's hand size and kinematic profile. Therefore, we built the entire hand module based on a set of key dimension parameters (Table 2). The parameters, after being measured from the user, can be

Table 2. Dimension Parameters and Illustration of the Kinematic Hand Model Used for the Design and Tailoring of RELab Tenoexo



1	Thumb length	11	Wrist to CMC thumb lateral
2	Index finger length	12	Wrist to CMC thumb distal
3	Middle finger length	13	MCP index to MCP thumb lateral
4	Ring finger length	14	MCP index to MCP thumb distal
5	Little finger length	15	Finger thickness at MCP
6	Wrist to MCP index finger	16	Finger thickness at PIP
7	Wrist to MCP middle finger	17	Finger thickness at DIP
8	Wrist to MCP ring finger	18	Thumb thickness at MCP
9	Wrist to MCP little finger	19	Thumb thickness at IP
10	MCP index to MCP little		

fed into the computer-aided design (CAD) model of the hand module, which then virtually rebuilds for the size of the individual user within 2–3 min.

Besides dimension parameters such as finger lengths and palm width, also functional parameters such as the wrist extension and ulnar deviation angles can be set to the user's functional abilities (e.g., increased joint stiffness or shortened wrist flexors due to tenodesis grip), as well as personal preferences. Kinematic relationships embedded in the CAD model ensure all kinematic functions of the hand module for any set of dimension parameters. This includes, for example, that the finger joints are aligned with the exoskeleton, that the fingers meet the thumb when full flexion is reached (in the case there is no interaction with any object), or that the hand module is aligned with the hand for all desired wrist flexion/extension and ulnar deviation angles.

Testing and Characterization

Grasp types and ROM

We identified the executable grasp types with a neurologically intact subject who was asked to grasp various objects with the help of RELab tenoexo. The test showed that the targeted four most frequently used grasp types (palmar pinch, medium wrap, parallel extension, and lateral pinch) could be executed with RELab tenoexo (Fig. 8b).

We tested the functionality of the executable grasp types by grasping objects with RELab tenoexo itself (no hand in the device). We chose objects from the standardized functional assessment action research arm test (ARAT[34]), which is used to assess the ability to handle 12 objects differing in size, weight, and shape and considered to be an arm-specific measure of activity limitation.[35] The hand exoskeleton could grasp 11 out of 12 objects ranging from a marble to a 7.5 cm wood block with ''full hand grasp'' or ''thumb only grasp'' (Fig. 8c). A 10 cm woodblock was not grasped. Eight out of the 11 grasped objects could be picked up directly from the desktop, 3 objects (a washer, a miniature ball, and a bolt) had to be fixed and placed in a certain position, such that RELab tenoexo could grasp them. In addition to the objects from the ARAT, the exoskeleton grasped and lifted a full 500 mL water bottle.

To achieve the required ROM, each joint is designed such that it can maximally flex 70°. However, the length of the actively sliding spring limits the overall flexion (sum of flexion in all joints). We therefore evaluated the ROM of the fingers measuring the overall finger flexion/extension angle, defined as the total angle over all joints from the center of the MCP joint to the fingertip (indicated as dashed line in Fig. 1a). Thumb flexion/extension was separated into CMC joint flexion/extension and a combined (overall) flexion/extension angle, including MCP and IP joints. The results are summarized in Table 3.

FIG. 8. **(a)** Functional grasp types that cover up to 80% of all grasping tasks performed in ADL[14] (denomination of Feix *et al.*[17]). **(b)** The four grasp types can be executed with RELab tenoexo. **(c)** The same grasp types can be used to grasp various objects with no human hand inside RELab tenoexo. ADL, activities of daily living.

Table 3. Range of Motion for Different Joints in [°]

	Flexion/extension		Abduction/adduction		Rotation
	CMC	Overall	CMC	MCP	CMC
Finger	n/a	−15 to 90	n/a	0 to 20	n/a
Thumb	−5 to 25	−10 to 45	0 to 45	n/a	0 to 50

n/a, not applicable; Overall, sum of MCP, PIP, DIP.

Maximal fingertip forces and control accuracy of the remote actuation system

To evaluate the force control accuracy and the maximal output force of the RAS, we increased the input force gradually and measured the resulting output force with a calibrated force gauge (LSB 302; FUTEK). A ramp function matches the load patterns of RELab tenoexo best and was tested at different angles of the RAS ranging from 0° to 150° in steps of 30° (Table 4). Forces were controlled with a mean absolute percentage error of below 5%. The maximal output forces of the RAS were 230 N for the wrist winch and 62 N for the thumb winch.

The fingertip force depends on the lever arm, which changes with different fingertip positions (overall finger flexion angle) and with different finger lengths. We therefore evaluated the fingertip force for different overall finger flexion angles and for the longest (middle) and shortest (little) finger. The input force was applied with a calibrated force gauge (Advanced force gauge AFG 100 N; Mecmesin Ltd., UK), depicted in Figure 9a. The force at the fingertip was measured with a spherical force sensor (OMD-10-SE-10N; OptoForce Ltd., Hungary). We measured the fingertip force at several overall finger flexion angles (10°, 30°, 90°, and 90°) for increasing input force (10 N, 20 N, 30 N, 40 N, 50 N, and 60 N).

For low overall flexion angles, the measurement was stopped at lower input forces when extensive deformation of the finger was observed. For high angles, the measured fingertip force was zero for input forces up to 40 N as the finger was still flexing and the fingertip was not yet in contact with the spherical force sensor. The results for these measurements are shown in Figure 9b.

We measured the maximal fingertip force of the middle finger, the little finger, and the thumb when actuated with the RAS after RELab tenoexo was completely assembled. We used a similar setup as described above. This time, the input force was generated with the RAS. For this experiment, we selected an overall finger flexion angle of 30°. The measured forces are listed in Table 5. Figure 8c shows that the fingertip force was sufficient to lift heavy objects such as a 500 mL bottle.

Weight, dimensions, and battery runtime

Weight and dimensions of the hand module and the actuation unit are listed in Table 5. We evaluated the weight of the fully

Table 4. Force Control Accuracy for Different Angles of the RAS

Angle	[°]	0	30	60	90	120	150	Overall
MAPE	[%]	4.3	4.1	2.7	3.8	3.0	3.4	3.6

MAPE, mean absolute percentage error; RAS, remote actuation system.

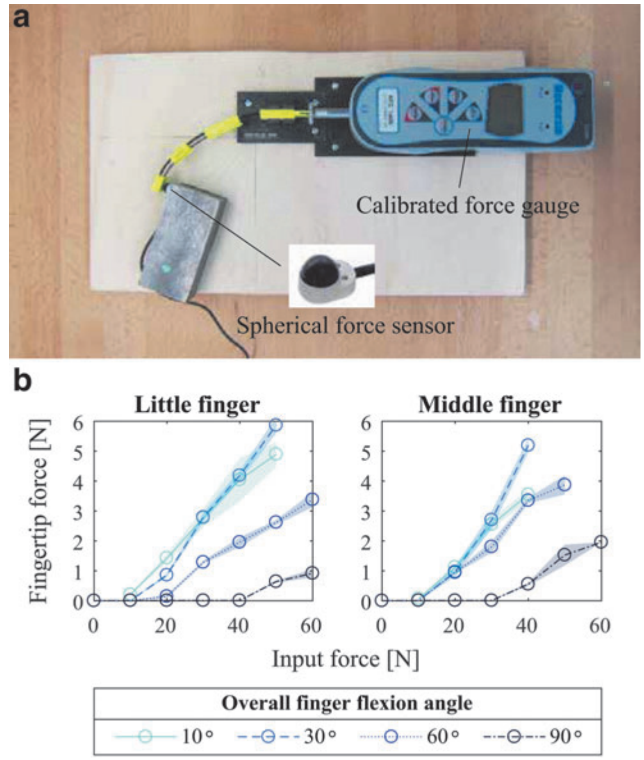


FIG. 9. **(a)** Measurement setup for fingertip forces in function of the finger flexion angle. The input force was applied with a calibrated force gauge, the fingertip force was measured with a spherical force sensor. **(b)** Fingertip forces (mean and standard deviation) in function of the input force and the overall finger flexion angle (total angle from the center of the MCP joint to the fingertip). Forces were measured for the little finger and the middle finger. The measurement was stopped at low input forces whenever extensive deformation of the finger was observed.

assembled hand module, including wrist and thumb winches, glove, and straps. We defined the length as the distance from tip of the middle finger to the most proximal point of the wrist, the width as the maximal distance perpendicular to the length, and the height as the maximal distance from the back of a user's hand, perpendicular to the user's hand. The weight and dimensions of the actuation unit are measured without battery. For the battery runtime test, we used a battery of 137 g.

The battery runtime (LiPo Akku, 11.1 V, 1.5 Ah, 137 g; Swaytronic, Switzerland) was assessed in a test bench with the fully assembled device. We continuously opened and closed the exoskeleton hand at a frequency of 0.5 Hz (one second to open and one second to close). After 1200 grasp cycles covering approximately 2 h of use, the battery voltage had dropped from 12.6 V to the nominal voltage of 11.1 V and needed to be recharged.

Automated tailoring algorithm

We built a total of five differently sized hand modules, which were modeled and dimensioned using the automated tailoring algorithm (three of which are displayed in Fig. 6b). We tested the hand size range for which the automated tailoring algorithm can be used by inserting dimension parameters from anthropometric databases[36] into the CAD model.

Table 5. Weight, Dimensions, Fingertip Forces, and RAS Output Forces of the Fully Assembled Hand Module (Black Hand Module as Presented in Fig. 3) and Actuation Unit

	Dimensions (LWH) (mm)			*Weight (g)*	F_{little} *(N)*	F_{middle} *(N)*	F_{thumb} *(N)*
Hand module	300	89	19	148	6.4	5.2	5.4
Actuation unit	156	104	39	492	57.5	57.5	62

LWH, length, width, height.

The CAD model rebuilt normally for hand sizes larger than those of 10-year-old subjects. Below this size, internal collisions occurred in the CAD model and the kinematic relationships could no longer be fulfilled.

User evaluation

Goal of the user test and protocol. We evaluated the immediate functional benefit and the usability in daily life for subjects with stroke and SCI in a pilot study with two subjects. We assessed the subjective impression with standardized questionnaires and custom-made questionnaires, and the functional benefit with the standardized functional assessment ARAT performed with and without the assistance of RELab tenoexo.

(1) Participants were asked to complete the quick disabilities of the arm, shoulder, and head questionnaire (quickDash[37]) to evaluate the subjective state of physical ability and symptoms.
(2) The hand exoskeleton was presented to the participants and they were asked to practice using the device for 20 min.
(3) Participants were asked to complete the ARAT without the hand exoskeleton, to assess their functional ability without assistance.
(4) Participants were asked to complete the ARAT with the hand exoskeleton, to assess their functional ability with assistance.
(5) Participants were asked to fill in the system usability scale (SUS)[38] and answer custom questionnaires to assess their subjective opinion of the overall usability of the hand exoskeleton.

Participants. One subject with chronic stroke (10 years after stroke event) and one subject with SCI (4 years after SCI event) participated in the functional assessment test.

The subject with stroke had moderate hand impairments. The remaining ability allowed for mass flexion of the fingers, but led to difficulties, especially with hand opening. This subject reported that their hand impairments were a problem in daily life and this was reflected in the quickDash score of 50 out of 100 points.[39]

The subject with SCI had strong hand impairments (American Spinal Injury Association Impairment Scale (AIS) A, lesion height sub C6). The subject could actively flex the elbow, pronate/supinate, and flex/extend the wrist. The subject was not able to actively move the fingers. This subject reported that their hand impairments were a major problem in daily life and this was reflected in the quickDash score of 71 out of 100 points.[39]

Feedback and results. Trained clinicians evaluated the ARAT according to the guidelines for the assessment.[34] The 19 items of the ARAT lead to a maximum score of 57 points, which are divided into four subscales related to grasp (18 points), grip (12 points), pinch (18 points), and gross arm movement (9 points). Scoring takes into account the degree of completion of a task and the time needed to complete it. The results for this measurement (completing the ARAT with and without the assistance of RELab tenoexo) are shown in Table 6.

The subject with stroke rated RELab tenoexo with 30 points in the SUS (maximal score: 100), while the subject with SCI rated it with 65 points. Both subjects were able to don the device independently in $\sim$2 min (subject with stroke) and 3.5 min (subject with SCI), and doffed in less than 30 s. With the help of the tester, the device could be donned in less than 2 min for both subjects. After donning, both subjects were able to control the device seamlessly with the large-diameter pushbuttons and complete the ARAT, despite no prior experience with the device.

Discussion

In this article, we presented the design of RELab tenoexo, a sleek, lightweight soft hand exoskeleton for assistance in grasping tasks of daily living. We derived detailed requirements, reported the design implementation, and evaluated the performance of the exoskeleton in individuals with moderate to severely affected hand motor function. Thanks to various novel design features, including a compliant finger mechanism, a versatile thumb mechanism allowing for pad and side opposition, various control strategies, and an automated tailoring algorithm, our exoskeleton can provide assistance in the most frequently used grasp types. In comparison to state-of-the-art hand exoskeletons with similar functionality, RELab tenoexo is extremely compact and lightweight. It is fully wearable and, as there are no electronics in the hand

Table 6. Action Research Arm Test Scores of the Subjects With Stroke and Spinal Cord Injury for the Completion of the Test With and Without the Assistance of RELab Tenoexo

	Subtest				
	Grasp	*Grip*	*Pinch*	*Gross*	*Total*
Subject with stroke					
Unassisted	8	5	4	4	21
Assisted	9	6	1	4	20
Subject with SCI					
Unassisted	4	0	0	6	10
Assisted	10	7	2	6	25

Maximum score: 57 points. Gross: gross arm movement subtest. SCI, spinal cord injury.

module, it is water and dust proof up to the remote actuation unit, further promoting its application in daily life.

The compliant finger mechanism interacts with the user in an inherently safe manner and allows for flexibility in terms of hand size and joint alignment, which facilitates donning, as well as grasp shaping during object interaction. As a result, the hand wearing the exoskeleton naturally adapts to the shape of the object to be grasped, thereby increasing grasp robustness and removing the need for *a priori* knowledge of the object to grasp or for advanced control. The modular design with different attachment and control options, and an automated tailoring algorithm, ensures optimal assistance and adaptability to the individual user. For a subject with high-level SCI, the assistance of RELab tenoexo led to an immediate, clinically important functional benefit.

Kinematic properties and functionality

The exoskeleton fingers are compliant to misalignment and forces generated by the user. They follow a flexion sequence from proximal to distal joints upon contact with objects, according to the physiological kinematic chain.[25] The arrangement with a small angle between the fingers generates abduction of the fingers during flexion, following the first postural synergy.[26,40] The thumb mechanism allows for pad and side opposition. These DOF, which are rarely supported in state-of-the-art hand exoskeletons,[8,9] allow grasp types accounting for up to 80% of the variability in human grasping to be performed.

The mechanical evaluation showed that the device covers the ROM required for functional tasks.[41,42] The fingertip force is in the range of other state-of-the-art hand exoskeletons.[11,12,43–45] Heavier items, such as a full 500 mL water bottle, can be grasped. A drop in fingertip force could be observed for increasing overall finger flexion angles (especially above 60°), as a large portion of the input force is stored in the spring-like mechanism.

While inefficient in terms of power consumption, we selected this trade-off to produce higher maximal fingertip forces at low overall finger flexion angles. With this behavior, the exoskeleton fingers generate high fingertip forces for large and thus typically heavier objects (small flexion angle, storing little of the input force) and small fingertip forces for small objects. Therefore, besides adapting to the shape of the grasped object, the exoskeleton fingers inherently adapt the force to the object. This property highly facilitates the control of RELab tenoexo such that no force sensors are required in the hand module. The stiff v-shape exoskeleton fingers are further beneficial to keep the fingers of the user extended and lead to a functional open hand position when the exoskeleton is not powered.

The functional assessment with objects of the ARAT with only the exoskeleton (not worn by a user) showed that the grasp types and the fingertip forces are sufficient to accomplish a high percentage of functional tasks. This highlights the optimal kinematic interplay of thumb and finger mechanisms, correct kinematic sequence from proximal to distal, appropriate force adaptation, and meaningful shape adaptation to different objects.

Usability in daily life

RELab tenoexo combines advantages of the two most frequently used types of mechanisms for hand exoskeletons. Similar to rigid link structures, the three-layered spring finger mechanism applies forces only normal to the flexion/extension plane, which is beneficial for safe use and well-directed interaction forces. Nevertheless, its compliance, weight, and form factor are comparable to tendon-based mechanisms.[45–47] The weight and form factor of the entire RELab tenoexo are significantly below the recommended values in the literature[8,48] and state-of-the-art hand exoskeletons with the same functionality (actuated flexion/extension of all fingers, and actuated flexion/extension and abduction/adduction (opposition) of the thumb)[43,44,49–52] The hand modules are as lightweight as sensorized passive gloves (ca. 130 g, e.g., Rapael Smart Glove; Neofect) or passive whole hand orthoses (ca. 100 g, e.g., Saebo Glove; Saebo, Inc.). In contrast to whole hand passive orthoses, which constantly preload the fingers toward extension, RELab tenoexo actively assists flexion, assists extension only when desired, and assists thumb opposition.

The modular design of RELab tenoexo is beneficial for users with different residual abilities. The actuation unit can be placed on a desktop, mounted on a wheelchair, or mounted as a backpack with harnesses of different sizes. Depending on the use (e.g., sporadically for certain tasks such as eating a meal or for use during the entire day), a different option can be chosen. The hand module can also be fixed in various ways upon the user's preference. If desired, individual fingers can be easily removed to assist only selected digits. The clip-on connection between the actuation unit and the hand modules allows the hand module to be donned without interfering with the Bowden cables.

The user can select from various control interfaces and control schemes. A user with unilateral paresis may use small push buttons located on the hand module and set the force with the slider on the control board. A user with bilateral paresis may use large push buttons mounted on the wheelchair, and select the forces through a trigger-controlled menu. Finally, the battery runtime (e.g., larger battery) and the duration of the closing movement (min. 1 s) can be selected.

For optimal assistance, the exoskeleton can be further tailored with the automated tailoring algorithm down to the size requirements of 10-year-old subjects. Besides size adaptations of the entire hand exoskeleton, the algorithm includes kinematic relationships that change with size to ensure optimal trajectories of the fingers and the thumb. A similar approach has been used by Bianchi M *et al.*,[53] who proposed an automated scaling procedure based on 3D motion capture.

User tests

The results from the user tests showed that the functional benefit largely depends on the residual ability of the user. The subject with stroke with moderate hand impairments performed slightly worse with support from RELab tenoexo. The distribution of the points in the subscales showed that the subject improved in the grasp and grip subscales, but performed worse in the pinch subtest. This result was expected, as finger individuation is needed to execute the items of the pinch subtest (pinch a marble with thumb and index finger, thumb and middle finger, and thumb and ring finger, respectively) and confirms that RELab tenoexo slightly limited the execution of dexterous tasks, but supported grip strength to grasp larger objects.

The subject with SCI with severe hand function impairments improved by 15 points with the support of RELab tenoexo. The minimal clinically important difference of the ARAT is 5.7 points and has been validated in subjects with chronic stroke.[54] Although this subject has SCI (for which the test has not been specifically validated), this result likely indicates a significant immediate positive effect on the functional ability. The subject with SCI could pinch the marble between index finger and thumb, which was not possible without the device. Visual inspection of recorded Supplementary Video S1 indicates that the compensatory movements required to grasp objects were largely reduced. Both subjects had the same score in the gross movement subtest of the ARAT with and without RELab tenoexo, indicating that the ROM of the arm is unrestricted.

From the questionnaires, we conclude that the weight of the hand module and the remote actuation unit is not perceived as limiting.

The subject with SCI appreciated the functional benefit and stated that they would use the device sporadically in daily life. Due to contractures, this subject normally keeps the hand closed in a fist, and therefore criticized that full closing of the hand to a fist is not possible. However, this subject explicitly mentioned that the different grasp types, which were possible because the hand did not close to a fist, were a very positive experience. The system would be more usable with reduced donning time to a few seconds and full integration into the wheelchair. Both demands can be addressed with further user-centered design. When asked what RELab tenoexo could be used for, this subject mainly listed unimanual tasks such as picking and placing objects, writing, or using tools (e.g., forks and knives). In bimanual tasks, for this subject, RELab tenoexo could support the more dexterous hand, while the unassisted hand could serve as a support hand.

For the subject with stroke, the perceived benefit was limited. In addition, this subject did not like the idea of being supported by a robot and stated that a hand exoskeleton should not be recognized as such. However, this subject also appreciated the functional benefit in the items of the grasp and grip subscales of the ARAT. When asked what RELab tenoexo could be used for, this subject mainly listed bimanual tasks. This indicates that, in contrast to the subject with SCI, for this subject, the device could be used to stabilize the support hand, while the sound hand is used for dexterous tasks.

The SUS scores reflect the overall usability for the two participants; however, the interpretation of the SUS score as single value is limited due to its subjective nature. According to Bangor *et al.*,[55] the results indicate fair usability (65 points) for the subject with SCI and poor usability (30 points) for the subject with stroke. We believe that a main limiting factor was the short training period. During the assessment, the participants not only kept improving their hand location and timing to grasp objects but also kept improving the overall handling of the device. Furthermore, the training did not include donning and doffing of the device, nor did it include finding the best location for the actuation unit—points that largely influenced the subjective perception of usability.

Limitations

With up to 6.4 N per finger, the fingertip forces were considerably below the target force of 10 N. It should be considered, however, that the forces suggested in literature were assessed in neurologically intact subjects.[56–58] As the generated forces were sufficient to complete the tasks of the ARAT and lift a 500 mL bottle, we conclude that lower forces in the range of the measured up to 6.4 N are sufficient to grasp and lift objects, and to complete most grasping tasks in ADL. We speculate that the grasp would be more secure (close to natural) with higher forces. This is subject to further user testing and refined finger design. High friction losses in the finger mechanism should be addressed to increase the efficiency, the battery runtime, and the fingertip forces.

In the user tests, missing finger individuation led to a low score in the pinch subtest. We selected actuated mass flexion of fingers, which adapt to shapes of objects as a trade-off with regard to simplicity of the device. Adding DOF necessary to perform highly dexterous tasks would increase the mechanical complexity of the system. More importantly, it would increase the control complexity to an extent which, thus far, cannot be controlled intuitively.

In the current prototype, the wrist is immobilized in a fixed functional position according to the findings in literature[32,59] to reduce complexity and limit weight. In the future, actuated wrist function could reduce the need for compensatory movements.[27] In addition, actuation of thumb abduction/adduction should be considered. However, these changes would come at the cost of a more complex and heavier design.

The used Bowden cables are custom made and currently have a limited durability of ~3200 grasp cycles. Refined cable guiding is required to increase the durability. Although RELab tenoexo was designed as a simple and lightweight device, it consists of ~100 individual parts, which make the initial assembly cumbersome. This is a limitation with regard to the fast production of the tailored parts from the automated tailoring algorithm. The continuous advances of 3D printing technology will likely overcome this limitation over time.

The user tests indicate an overall benefit for the subject with SCI and a benefit in grasping tasks for the subject with stroke. More user tests with various subjects and different functional abilities need to follow to assess the full potential of RELab tenoexo.

Conclusion

To optimize the difficult trade-off between functionality and usability in daily life typical for assistive technology, RELab tenoexo successfully reduces the complexity of the human hand to the most relevant functions in a lightweight and low-profile design. Advantages of rigid link structures and soft tendon-based mechanisms are combined with kinematic considerations and allow subjects with neuromotor hand impairments to be assisted in the most frequently used grasp types in ADL. We identified an immediate clinically important functional benefit in a subject with SCI and improvement of grasp function in a subject with stroke. With a user-centered approach, high overall usability was targeted, including modularity, tailorability, waterproofness, cleanability, and ergonomic, appealing design.

Future work should include even further personalization of the functions, the appearance, and the control of the device to the specific needs and wishes of the user. As one of the only fully wearable hand exoskeletons allowing for pad and side opposition of the thumb, RELab tenoexo is a promising candidate for grasping assistance in daily life for people with severely affected hand motor function, low residual grasp force, low active control of the hand, low spasticity, low muscle tone, and residual proximal arm function.

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Supplementary Material

Supplementary Video S1

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