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Design and feasibility of the T-GRIP thumb exoskeleton to support the lateral pinch grasp of spinal cord injury patients

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***Abstract*— Improving the impaired hand function of spinal cord injury patients with a robotic exoskeleton can highly impact their self-management, and ultimately their quality of life. In this paper the design and evaluation of a new, lightweight (50 gram) robotic thumb exoskeleton, called T-GRIP, was presented that supports the lateral pinch grasp. The mechanism consists of a linear actuator that was mounted to the dorsal side of the hand, and a force transmission mechanism that flexes the thumb towards the side of the index finger. The thumb movement was controlled through contralateral wrist rotation. Experimental results from an evaluation with three spinal cord injury patients showed that the achieved grip force (˜7N) was higher and the overall performance during the Grasp and Release Test was better with the T-GRIP than without device. The device shows great potential for improving the hand function of patients with cervical spinal cord injury by actuating only a single degree of freedom.**

I. INTRODUCTION

A spinal cord injury (SCI) can be traumatic (e.g. due to falls, road traffic accidents or sports) or non-traumatic (e.g. due to bleedings, infections, tumors or degenerative diseases). The incidence of traumatic SCI is estimated to be 14-16 per million per annum in Western Europe [1], [2]. The incidence of non-traumatic SCI is unknown but assumed to be slightly higher than the incidence of traumatic SCI [3]. More than 69% of the traumatic cases are cervical lesions (tetraplegia) [1]. Depending on level and severity of injury, the motor and sensory function of the upper extremities might be affected. 77% of the tetraplegic subjects expect an important or very important improvement in their quality of life if their hand function would improve [4].

Several assistive, robotics devices are available to support the impaired hand function following SCI, including recent developments such as proposed in prior research [5]–[8]. Most of these devices support the hand by enabling a cylindrical grasp which requires at least two or more fingers to be actuated. An extensive review of the current state of the art is presented in [9].

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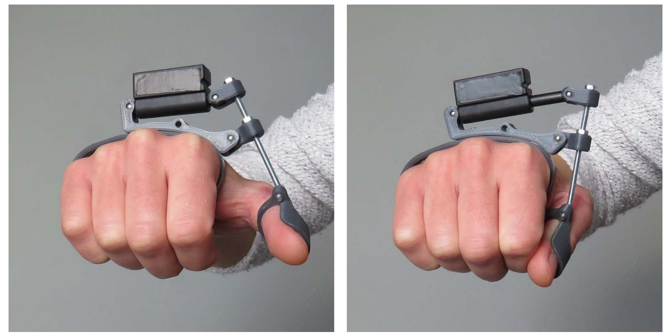

Fig. 1: Overview of the T-GRIP thumb exoskeleton that supports the lateral pinch grip. The force transmission mechanism is shown with the thumb in extended (left) and flexed (right) position.

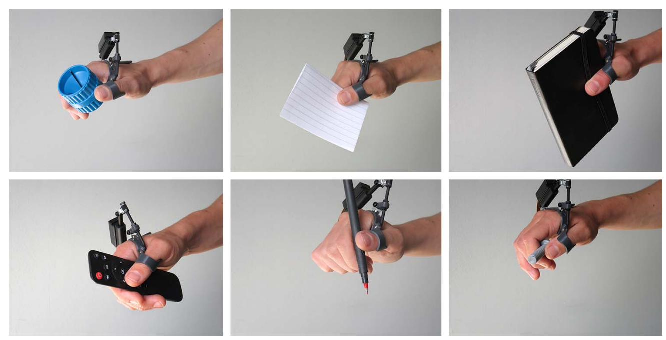

Fig. 2: The T-GRIP enables grasping of various objects of different size and shape, including cylindrical, flat and irregular shaped objects.

Reconstructive surgery can (partially) restore impaired hand function by transferring tendons [10] or nerves [11]. However, this change is permanent and the procedure is invasive. In a survey study by Wagner et al., the factors of risks and recovery time have been shown to influence the desire to undergo surgical procedure among 62% and 52% of the interviewed SCI patients [12].

In this paper we present the design and evaluation of a new robotic thumb exoskeleton, called T-GRIP, that solely supports the lateral pinch grasp. For most spinal cord injury patients, this grasp is considered the most useful one to be restored [13]. In lateral pinch, objects are clamped between the thumb and the side of the index finger. Our design approach helps to deal with the most important factors to consider in assistive hand exoskeleton design such as wearability, low weight and comfort [9]. Compared to other assistive devices that support for example the cylindrical or tripod grasp, our new mechanism provides functional support with minimal hardware as only one degree of freedom (one

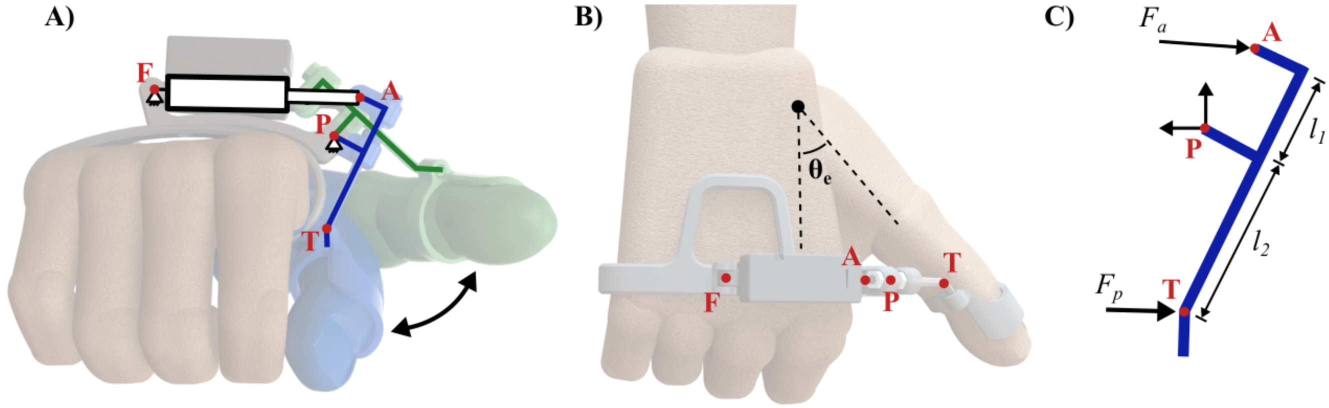

Fig. 3: A) Schematic overview of the T-GRIP mechanism mounted on the hand while the lever arm causes the thumb to be in extended (green) and flexed (blue) position (frontal view). The lever arm rotates around the pivot point (P) and secures the tip of the actuator (A) to the thumb (T). The actuator is suspended on the hand at point (F). B) Top view of the hand in opened position, showing the thumb extension angle (θ_e). C) Free body diagram of the lever arm of the T-GRIP mechanism. Actuator force (F_a) causes the lever arm to rotate around the pivot point, resulting in a force (F_p) at the distal point of the lever arm. Varying the ratio between l_1 and l_2 will affect the resulting force F_p and the thumb range of motion.

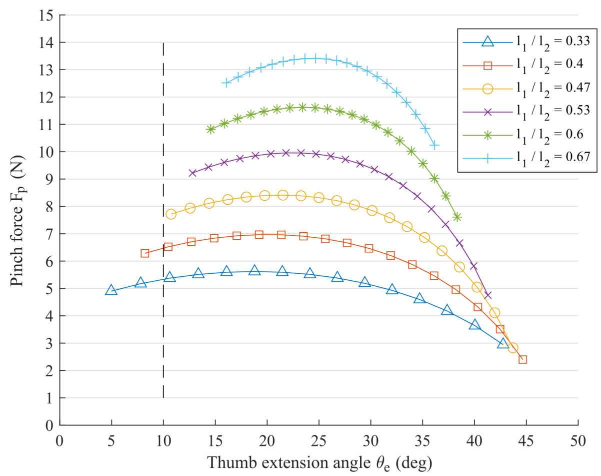

Fig. 4: Plot showing the thumb extension angle θ_e (°) versus pinch force F_p (N) for different lever arm ratios (l_1 / l_2). The dashed line indicates the approximate thumb extension angle at which the thumb and index finger touch.

thumb rotation) needs to be controlled. The other fingers are assumed to stay in place (or will be fixated).

First, an overview of the mechanical design including kinematic analysis is presented, followed by the experimental procedure and the results from an evaluation with 3 patients.

II. THUMB EXOSKELETON

A. Mechanical design

The hand-mounted part of the exoskeleton (see Fig. 1) consists of a thermoplastic hand bracket onto which an electric micro linear actuator (Actuonix Motion Devices Inc., Canada) is attached. This actuator has a weight of 15gr., a stroke of 20mm and provides a maximum force of 40N. To accommodate a pinch grasp, the linear actuator pushes on a lever arm which moves a thumb ring to the index finger. The hand bracket and thumb ring can be adjusted to fit the user's hand. Hyperextension of the distal joint of the thumb is prevented by the thumb ring design.

A lateral pinch grip requires a flexed index finger to provide a stable counterpart for the grasping movement. If the user is unable to maintain a flexed index finger position, or if the passive stiffness in medio-lateral direction is limited, an additional bracket can be used to stabilize the finger in the desired flexed position. The total weight of the hand-mounted part is 50 grams. The maximum height of the mechanism above the hand is 40 mm. The device accommodates grasping of objects of different size and shapes, see also Fig. 2.

The linear actuator is suspended on the dorsal side of the hand at point F, see 3A. The lever arm hinges around point P and is on one end connected to the actuator (at point A) and on the other end to the thumb ring (at point T).

To successfully grasp and manipulate thin objects with the lateral pinch grasp, the tip of the thumb should be able to touch the side of the index finger. Depending on the width of the index finger and thumb, the thumb extension angle θ_e (Fig. 3B) at which the thumb touches the side of the index finger is approximately 10°. The maximum extension of the actuator should therefore move the thumb to an extension angle of 10° or less, while the minimum extension of the actuator should not cause the thumb to exceed the maximum comfortable extension angle limit of approximately 40 - 50°. This is dependent on the maximum passive thumb extension of the patient.

A kinematic model was derived (Appendix) to calculate the thumb range of motion and pinch force for any configuration of the mechanism. The range of motion of the mechanism can, among others, be adjusted by changing the lever arm ratio (l_1 / l_2), see Fig. 3C. As an illustration of this effect, in Fig 4 the pinch forces are plotted as a function of the thumb extension angle for varying lever arm ratios (l_1 / l_2) while keeping the total lever arm ($l_1 + l_2$) length equal. The configuration that was used for this calculation was: F_a = 40 N, l_1+l_2=50 mm, l_{fx}=50 mm, l_{fy}=25 mm, l_a=8 mm, l_p=10 mm, β=15 °. See also Appendix for a detailed description of all relevant model parameters. From Fig. 4 it can be seen that decreasing the lever arm ratio will increase

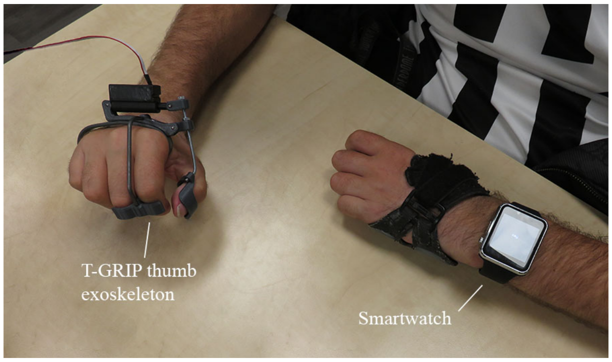

Fig. 5: Flexion and extension of the T-GRIP thumb exoskeleton is controlled with the programmable smartwatch that is worn on the contralateral wrist.

the total range of motion, and causes a smaller minimum θ_e to be reached. Thus, for smaller lever arm ratios smaller objects can be grasped. However, the maximum pinch force (F_p) will decrease as the ratio decreases.

B. Control strategy

The actuator movement direction of the exoskeleton is controlled by rotating a 32-bit programmable smartwatch (LilyGo, CN) that is worn on the contralateral wrist, see Fig. 5. The smartwatch contains a digital, triaxial acceleration sensor that measures wrist orientation which is then sent over Bluetooth Low Energy to a discrete state machine (see Fig. 6) that is implemented on an ESP32 microcontroller (LilyGo, CN). Wrist pronation starts a flexion movement and wrist supination triggers thumb extension by sending a PWM signal to the motor that determines the average value of the output voltage. Thumb movement is stopped if the wrist is put into neutral position, or if the actuator soft end stop is reached. The electronics and battery are contained in an enclosure (170 gr, 80x150x35 mm). The exoskeleton is powered by a rechargeable 6V battery (Ni-MH, 350 mAh).

III. EXPERIMENTAL PROCEDURE

The goal of the feasibility study was to evaluate the technical viability of the T-GRIP thumb exoskeleton when used by SCI patients. During this session pinch force measurements, the Grasp and Release Test and the D-QUEST questionnaire about the user satisfaction with the device were conducted.

Three tetraplegic patients (AIS A/B) were recruited from Roessingh, Center for Rehabilitation (Enschede, the Netherlands). Other inclusion criteria included: $\geq$ 18 years, weakness of finger flexors (Medical Research Council muscle power $\leq$ 2, and normal passive range of motion of the thumb. Contra-indications for the participants were: increased tone or spasticity in the arm and hand, severe contractures or joint deformities in the fingers, open wounds and infected areas of the hand, recent arm or hand surgery (<6 months) or lack of active contralateral wrist pronation and supination. Ethical approval for this study was obtained from the Ethics Committee of the University of Twente (ref. number 2021.12995). Written informed consent was obtained from all participants before the study onset. During fitting, only lengths l_1 and l_2

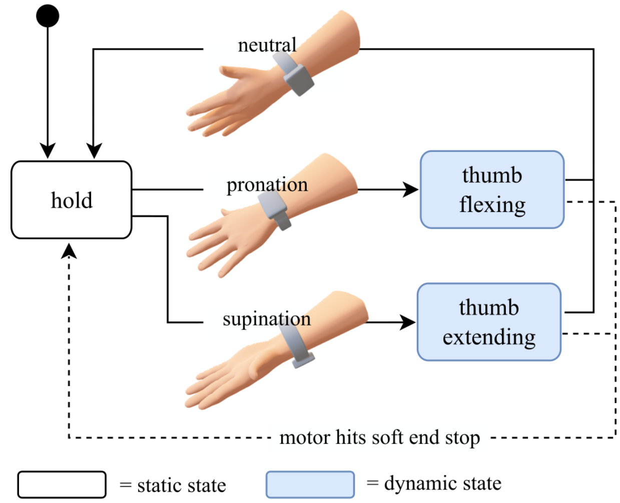

Fig. 6: Discrete state machine of the exoskeleton control showing the possible transitions from the static state (hold) to the dynamic states ('thumb extending' and 'thumb flexing'). Actions to transition between these states are written next to the arrows. Pronation of the contralateral wrist controls thumb flexion. A neutral position stops the motor. Supination of the contralateral wrist controls thumb extension.

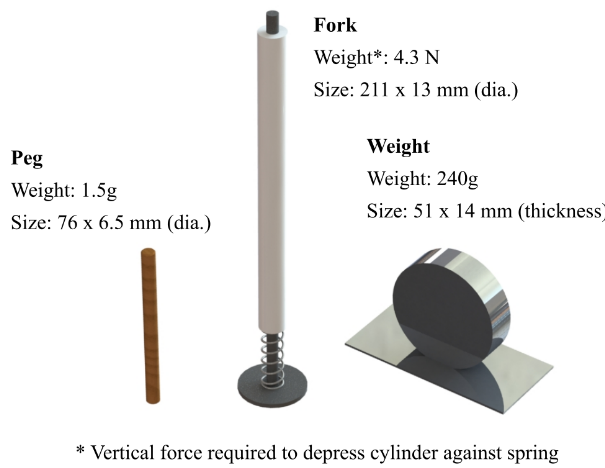

Fig. 7: 3D representation including specifications of the three objects of the Grasp and Release Test that are handled with a lateral pinch grasp. These are: peg, fork and weight.

of the lever arm were customized for each patient. The other parameters were kept the same.

A. Pinch force

The peak and sustained pinch grip force were assessed firstly without, and then with the thumb exoskeleton. Subjects were instructed to hold and squeeze an E-link Pinchmeter (Biometrics Ltd, USA) during a 10-second period. Each condition was repeated three times and the average peak force and average force over the last 60% of the measurement were reported per participant.

B. Grasp and Release Test

The Grasp and Release Test (GRT) measures the unilateral hand function during object manipulation and is validated for SCI patients [14], [15]. For this study, three (out of six)

TABLE I: Baseline characteristics of participants

	Age	Gender	Dominant hand	Exo	SCI level		
					AIS	Motor	Sensory
P1	39	M	Right	Right	B	C5	C6
P2	26	M	Right	Right	A	C5	C4
P3	39	F	Right	Left	A	C6	n/a

SCI: Spinal Cord Injury; AIS: American Spinal Injury Association Impairment Scale; M: male; Motor: motor level of injury; Sensory: sensory level of injury; F: female; C[1-7]: cervical vertebra that defines the level of injury.

TABLE II: Average maximum and sustained pinch grip strength measured without and with the exoskeleton across three measurements. Sustained pinch force is the mean pinch force over last 60% of 10s pinch force measurement;

	Maximum pinch force (N)		Sustained pinch force (N)	
	No exo	With exo	No exo*	With exo
	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
P1	0.0 (0.0)	7.2 (0.5)	-	6.5 (0.5)
P2	0.7 (0.5)	7.8 (0.0)	-	6.5 (0.5)
P3	0.0 (0.0)	1.3 (0.5)	-	1.3 (0.5)

* Participants were unable to reach the threshold (1N) that triggered the start of the sustained force measurement with the E-Link pinchmeter. SD: standard deviation.

objects of the GRT were chosen that require a lateral pinch grasp: peg, fork and weight (see also Fig. 7). These objects vary in size, weight and surface texture. The sequence of movements for the peg and weight equals 'grasp', 'lift', and 'release'. The sequence of movements of the fork equals 'depress handle', 'lift' and 'release'. For each object, the corresponding sequence was executed by the subjects as many times as possible in 30 seconds and the number of successful completions were scored. In total three trials per object were performed. Between trials there was a 30-second resting period. For the peg a successful completion involved dropping the item in the test box (20x20x4.5cm) without touching the side of the box. The fork should be pressed down to the indicator line, while the weight should be placed upright on top of the test box for a successful completion. For each participant, the mean number of successful sequence completions performed in 30 seconds across three trials were reported per object.

C. User satisfaction

The satisfaction of the participants with the assistive device was rated with the Quebec User Evaluation of Satisfaction with Assistive Technology (QUEST) questionnaire [16]. The first eight items of this questionnaire relate to the assistive device, and were scored on a scale from 1 (not satisfied at all) to 5 (very satisfied). The question related to the durability was left out of the investigation, because the use period was too short to rate this aspect.

IV. RESULTS

A. Participants

Three SCI patients participated in the study. Their characteristics are listed in Table I. Participant P1 required an additional bracket to keep his index finger in a flexed position. Participant P2 required a static wrist splint as his wrist extensor muscles could not keep his wrist in a neutral position when grasping (heavy) objects.

B. Pinch force

The results of the maximum and sustained pinch force measurements are reported in Table II. For all participants, the maximum pinch force measurement with exoskeleton was higher than without exoskeleton. For participant P3, the maximum pinch force measurement with exoskeleton was much lower than for the other two participants. All three participants were unable to reach a threshold of 1N that triggered the start of the sustained pinch force measurement with the E-Link Pinchmeter software. Still, it can be concluded that the sustained pinch force with exoskeleton was higher than without exoskeleton.

C. Grasp and Release Test

The Grasp and Release Test (see Fig. 8) was conducted to observe the difference in ability of participants to grasp and release standardized objects with and without the thumb exoskeleton. The mean number of successful completions across three trials ($N_{success}$, see also Fig. 8) show that all participants were able to successfully grasp the pegs without exoskeleton. For two participants, the mean number of successful peg sequence completions was lower when the exoskeleton was used. None of the participants were able to successfully grasp the fork and weight without exoskeleton. In contrast, all participants were able to grasp the fork and weight with exoskeleton.

D. User satisfaction

To evaluate user satisfaction, the Quebec User Evaluation of Satisfaction with assistive Technology (QUEST), was conducted after the measurements. In Table III the questions and scores are reported per participant. Also a mean score per aspect was calculated. The results from the questionnaire reported a high level of satisfaction (range 3.7-4.3). Users are

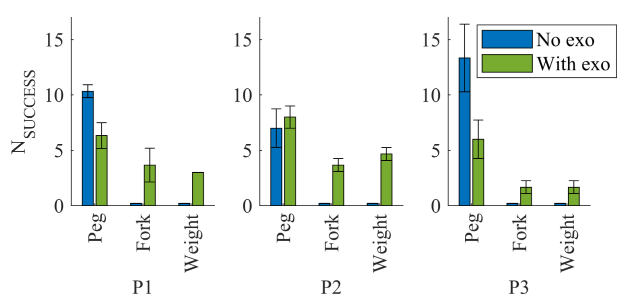

Fig. 8: The results of the Grasp and Release Test for each participant and object showing the mean number of successful completions ($N_{success}$) in 30 seconds across three trials without (blue) and in with (green) the exoskeleton.

TABLE III: User satisfaction results from QUEST questionnaire

How satisfied are you,	P1	P2	P3	Mean score
1. with the dimensions (size, height, lengths, width) of your assistive device?	5	3	4	4
2. the weight of your assistive device?	5*	3*	4	4
3. the ease in adjusting (fixing, fastening) the parts of your assistive device?	5	4	3	4
4. how safe and secure your assistive device is?	5	4	4	4.3
5. how easy it is to use your assistive device?	5*	4	3	4
6. how comfortable your assistive device is?	5	3*	3	3.7
7. how effective your assistive device is (the degree to which your device meets your needs)?	5*	4*	4	4.3

1: not satisfied at all; 2: not very satisfied; 3: more or less satisfied; 4: quite satisfied; 5: very satisfied; * = most important aspects of an assistive device according to user.

most satisfied with the safety (4.3) and effectiveness (4.3) of the device. Comfort was rated lowest (3.7). According to the participants, the most important aspects were *weight*, and *effectiveness*, followed by *ease of use* and *comfort*.

V. DISCUSSION

Supporting the impaired hand function of SCI patients with a robotic exoskeleton can highly impact their self-management, and ultimately their quality of life. In this study, the design of a new, lightweight thumb exoskeleton, T-GRIP, was presented that supports the lateral pinch grasp. The mechanism consists of a force transmission mechanism that moved the thumb towards the side of the index finger. The exoskeleton focuses on enabling the core functionality required to regain basic functional performance.

Experimental results from an evaluation with three SCI patients showed that the pinch force improved when using the exoskeleton. Also, their ability to successfully grasp and manipulate objects of different sizes and weights was improved. The low weight (50 gr.) of the hand-mounted part is another advantage of the device. The average weight of comparable hand exoskeletons found in literature is approximately 200 gr. [9]. The evaluation revealed a high degree of satisfaction with the device. Although these conclusions are based on only three participants, the results still provide valuable insights and suggestions for improvements such as increasing the speed and personalize the fitting. A clinical study with more participants should be performed to further investigate the functionality and usability of the system.

Limitations of the study were a sub-optimal fitting procedure and a limited number of participants. A peak pinch force of more than 7N was measured for two participants. For participant P3, the measured force was much lower 1.3N. This may have been caused by the small hands of this patient. For participant P3, the fitting procedure might have been not optimal, leading to incomplete flexion of the thumb and therefore insufficient pinch force. This emphasizes that it is essential to personalize the thumb exoskeleton based on more parameters besides the lever arm ratio, for example the position of the mechanism with respect to the hand (l_{px}, l_{py}, l_{pz}), the position of the actuator (l_{fx}, l_{fy}), or lever arm parameters (l_a, l_p, β), see Fig. 9. The order of the test execution was not randomized due to the small sample size. Potential fatigue could have biased the results. However, as the evaluation with the exoskeleton was always performed after the evaluation without exoskeleton, it is unlikely that the results were positively biased towards the exoskeleton. The additional bracket that may be used to help maintaining a flexed index finger also provides support of the index finger in medio-lateral direction. Not using a bracket thus could have affected the maximum grip force of the two participants that did not use the bracket, as the pinch force will be lower if the index finger is pushed medially by the thumb. Future work should include a larger and more diverse sample size to provide more conclusive results about the potential benefit of the T-GRIP exoskeleton.

Even with weak motor function, grasping and manipulation of lightweight objects is often still possible for SCI patients by utilization of the natural tenodesis effect [17]. In fact, the addition of the thumb exoskeleton decreased the performance for two participants during the peg object of the Grasp and Release Test, as the speed of the linear actuator (max. no-load speed of 10mm/s limited the speed of the test execution. For heavier objects such as the fork and weight during the Grasp and Release Test, the thumb exoskeleton improved the performance. In a future study the limiting effect of the actuator speed will be investigated.

Of all device aspects, comfort was rated lowest (3.7 out of 5) by the three participants. Improvements that could increase the comfort are to use padding between the hand bracket and the skin, and to further personalize the fitting procedure.

All three participants were able to easily control the thumb exoskeleton through contralateral wrist rotation after a 3-minute training period. This indicates that the used control strategy is intuitive. However, the strategy decreases the employability of their contralateral hand during bimanual tasks or trunk stabilization. For users with low residual hand function, or during unilateral tasks, this might not be a problem, but in other cases this is not desired. In the future, we will explore alternative control strategies such as voice control to bypass this problem. Also, it would be interesting to add a feedback modality, but this may be complicated due to a decreased sensitivity of the fingers.

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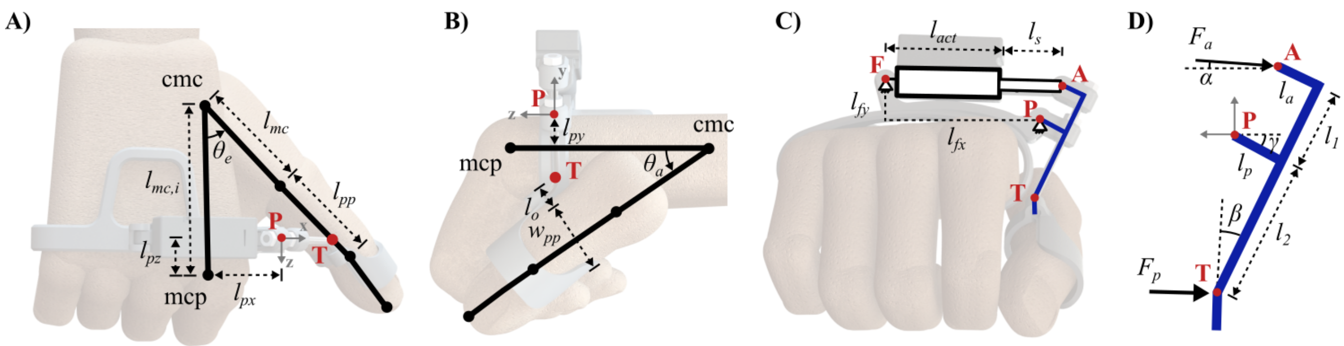

Fig. 9: A) Top view of the hand with the thumb extended by angle θ_e. B) Side view of the hand with the thumb in flexed position, and abducted by angle θ_a. C) Front view of the hand with the actuator fully extended such that the lever arm (blue) flexed the thumb. The actuator (length l_{act} and stroke l_s) is suspended at a distance (l_{fx}, l_{fy} from pivot point P. D) Close-up of the lever arm. Actuator force (F_a) causes the lever arm to rotate around the pivot point (P), resulting in a force (F_p) at the distal point of the lever arm (T).

APPENDIX

A kinematic model of the thumb and the exoskeleton was derived to calculate the pinch force (F_p) and the thumb angles (θ_e and θ_a) for any mechanism configuration. In Fig. 9, all relevant model parameters are shown. The closed-form expression of F_p was found from the moment equilibrium of forces F_a and F_p acting around point P:

$$F_p = F_a \frac{l_1}{l_2} \cos(\gamma - \alpha) \cos\beta \tag{1}$$

Actuator and pivot (α and γ) angles were numerically solved (using MATLAB's routine *fsolve*) by minimizing sum of the squared function values of the system of equations S_1:

$$S_1(\alpha, \gamma) = \begin{cases} -l_{fx} + (l_{act} + l_s)\cos\alpha - \\ (l_p \cos\gamma - l_1 \sin\gamma - l_a \cos\gamma) = 0 \\ l_{fy} + (l_{act} + l_s)\sin\alpha - \\ (l_p \sin\gamma + l_1 \cos\gamma - l_a \sin\gamma) = 0 \end{cases} \tag{2}$$

The thumb angles (θ_e and θ_a) were numerically solved (using MATLAB's routine *fsolve*) by minimizing sum of the squared function values of the system of equations S_2:

$$S_2(\theta_a, \theta_e) = \begin{cases} T_x - (l_p \cos\gamma + l_2 \sin\gamma) \\ T_y - (l_p \sin\gamma - l_2 \cos\gamma) \end{cases} \tag{3}$$

Here, T is the interface point between mechanism and thumb:

$$T = R_x(\theta_a) R_y(\theta_e) \begin{bmatrix} -(\frac{w_{pp}}{2} + l_o) \\ 0 \\ l_{mc} + r l_{pp} \end{bmatrix} + \begin{bmatrix} -l_{px} \\ -l_{py} \\ l_{pz} - l_{mc,i} \end{bmatrix} \tag{4}$$

R_x and R_y are the basic 3D rotation matrices around the x- and y-axis, w_{pp} is the thumb proximal phalanx width, l_o is an offset from the skin, l_{mc} and l_{pp} are the metacarpal and proximal phalanx thumb lengths, and r is a fraction. l_{px}, l_{py}, l_{pz} are the MCP joint coordinates relative to P, and $l_{mc,i}$ is the index finger metacarpal bone length.

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