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Mechanical Design and Feasibility of a Finger Exoskeleton to Support Finger Extension of Severely Affected Stroke Patients

Claudia J. W. Haarman, Edsko E. G. Hekman, *Member, IEEE*, Johan S. Rietman, and Herman Van Der Kooij, *Member, IEEE*

***Abstract*— In this paper we presented the mechanical design and evaluation of a low-profile and lightweight exoskeleton that supports the finger extension of stroke patients during daily activities without applying axial forces to the finger. The exoskeleton consists of a flexible structure that is secured to the index finger of the user while the thumb is fixed in an opposed position. Pulling on a cable will extend the flexed index finger joint such that objects can be grasped. The device can achieve a grasp size of at least 7 cm. Technical tests confirmed that the exoskeleton was able to counteract the passive flexion moments corresponding to the index finger of a severely affected stroke patient (with an MCP joint stiffness of k = 0.63Nm/rad), requiring a maximum cable activation force of 58.8N. A feasibility study with stroke patients (n=4) revealed that the body-powered operation of the exoskeleton with the contralateral hand caused a mean increase of 46° in the range of motion of the index finger MCP joint. The patients (n=2) who performed the Box & Block Test were able to grasp and transfer maximally 6 blocks in 60 sec. with exoskeleton, compared to 0 blocks without exoskeleton. Our results showed that the developed exoskeleton has the potential to partially restore hand function of stroke patients with impaired finger extension capabilities. An actuation strategy that does not involve the contralateral hand should be implemented during further development to make the exoskeleton suitable for bimanual daily activities.**

***Index Terms*— Exoskeleton, finger extension, assistive device, wearable.**

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I. Introduction

STROKE is one of the leading causes of permanent disability among adults. In 2017, 1.12 million incident strokes occurred in Europe [1]. Many stroke patients experience hand motor impairments such as decreased grip strength and finger extension impairment. Approximately 65% of the stroke patients do not involve their impaired hand during daily activities 6 months post-stroke [2]. Factors contributing to a loss of hand function after stroke may include extensor muscle weakness, increased flexor muscle tone, spasticity and contracture [3], [4]. These symptoms typically causes the hand to be clenched, which affects the patient's ability to perform (bimanual) activities of daily living (ADL).

Assistive hand exoskeletons can support the impaired hand of stroke patients with reduced finger extension capabilities to improve the execution of bimanual tasks. Three common approaches are found in literature that are specifically aimed at extending the finger during daily activities using portable hand exoskeletons. (Exoskeletons focusing primarily on grasping assistance are not regarded in this overview.) 1) Cable-driven finger extension exoskeletons use cables that are routed on the dorsal side of the finger through a glove [5], [6], [7], [8]. Donning glove-based designs is considered challenging and is typically not possible without assistance [9]. Also, inherent to their design, these devices exert high, undesired, axial forces to the fingers during extension. 2) In pneumatic hand exoskeletons [10], [11] no rigid structure is present to guide the extension torques to the finger, therefore misalignment may lead to secondary injuries or discomfort [12]. Additionally, bulky and heavy actuators are required to provide the large extension torques necessary to extend the fingers of stroke patients. This limits the portability of pneumatic exoskeletons. [12]. 3) Spring-operated finger extension devices include the SaeboFlex [13] and SaeboGlove (Saebo Inc., USA). These devices rely on the stiffness of normal extension springs or rubber bands to extend the fingers. In order to grasp objects, patients require high voluntary flexion torques to overcome the (high) spring stiffness. If patients cannot provide sufficient flexion torques, then the functional benefit of these spring-operated extension devices during ADL is limited.

In the Hand Spring Operated Movement Enhancer (HandSOME) [14], shear forces on the finger are reduced by aligning the mechanism with the combined rotation axis of all proximal finger joints. The device is bulky, which limits the suitability of this device for daily activities. Several exoskeletons exist that consist of leaf springs (and multiple segments) mounted on the dorsal side of the finger [15], [16]. These mechanisms reduce the axial load on the finger and prevent hyperextension to some extent. However, the mechanisms are attached to a glove which makes donning difficult, and have limited power to provide extension of fingers with severe hypertonia.

In this paper we present the mechanical design and evaluation of a novel, lightweight assistive finger exoskeleton that supports the finger extension of stroke patients. The exoskeleton consists of a flexible structure that is connected to the index finger of the user in a two-step donning process. Simultaneous extension of the index finger and middle is also possible if these digits are strapped together. The thumb is fixed in an opposed position. By pulling on a cable the finger(s) is extended to provide enough hand opening to allow for object grasping, without applying axial forces to the finger. The required actuation forces to operate the extension mechanism were measured while being attached to a mechanical finger simulating a high finger joint stiffness. The orthosis-patient interaction was evaluated with four stroke patients in terms of kinematics and required cable forces. Also a performance-based test (Box & Block test) was conducted to investigate the difference in task execution between the supported and non-supported condition. To test the orthosis-patient interaction, participants used their contralateral hand to operate the extension mechanism.

II. Requirements

In this research a novel exoskeleton was developed with a small form-factor and low weight, that supports the finger extension of stroke patients during ADL without applying axial forces to the finger. The main requirements for this assistive device are summarized in Table I. An elaborate description can be found below.

TABLE I
Summary of Requirements for Exoskeleton to Support Extension of the Fingers During ADL

Requirement	Description
Maximum grasp size	Between 5 and 7 cm
Compensated MCP finger joint stiffness	$\geq$0.63 Nm/rad (when initiating movement from a resting angle of 40°)
Degrees of freedom	Enable precision and power grip
Wrist	Stabilized in functional position
Weight	<200g (hand-mounted part)
Size	<8 mm above dorsal surface of hand
Usability	Independent donning doffing
Axial forces	No axial forces applied to fingers
Adaptability	Fit adult hand sizes

A. Grasp Size

Patients with a high finger-joint stiffness will initiate their hand movement from a flexed position. Achieving a sufficient hand opening is crucial for enabling activities of daily living (ADL). Feix et al. found that a grasp size of 7 cm or less was sufficient for their observed (healthy) population to grasp 90% of the objects in a data set [17]. In 83% of the cases, the required grasp size was less than 5 cm. To accommodate grasping of a sufficiently large range of objects, it should therefore be possible to achieve a grasp size of at least 5 cm, and preferably 7 cm with the device. To achieve a hand opening of more than 5 cm with an average-sized finger, index finger flexion angles of approximately 10°(MCP) and 20°(PIP) are required. Here, a fixed thumb CMC abduction angle of 30° is assumed.

B. Finger Joint Stiffness

Antagonistic flexor and extensor muscles control the rotation of the metacarpophalangeal (MCP), proximal interphalangeal (PIP) and distal interphalangeal (DIP) joints of the finger (Fig. 1A). Mechanical resistance to rotation, or rotational stiffness (k), is expressed as the ratio of the change in moment (ΔM) to the change in joint rotation angle ($\Delta\theta$):

$$k = \frac{\Delta M}{\Delta \theta} \tag{1}$$

Depending on the severity of their impairments, the finger joint stiffness may vary considerably among stroke patients.

The Modified Ashworth Scale (MAS) is a clinical score commonly used to grade the degree of resistance against passive rotation of a joint on a scale from 0 (no resistance) to 4 (joint rigid in flexion or extension) [18]. MCP finger joint stiffness values associated with stroke range from approximately k=0.09-0.14 Nm/rad in mildly affected patients (MAS=1+), to k=0.52-0.54 Nm/rad in moderately affected patients (MAS=2), and up to k=0.63 Nm/rad in severely affected patients (MAS=3) [14], [19]. The associated MCP joint resting angle was 42° flexion for the most severe patient. For healthy controls, the measured finger joint stiffness values were significantly lower (between 0.03-0.05 Nm/rad) [19]. With this exoskeleton we aim to extend the fingers of mildly to severely affected patients. Therefore, the exoskeleton should be able to extend fingers with an MCP joint stiffness up to 0.63 Nm/rad.

C. Degrees of Freedom

The device should allow for the interaction with different types of objects to be useful in daily life. Both the precision and power grip are commonly used grasp modes during object manipulation [20]. For the precision grip, the object is clamped between the fingers and the opposing thumb. For the power grip, the object is clamped between the fingers and the palm of the hand, whereas the counter pressure is applied by the thumb [20]. The precision grip requires only one degree of freedom (DOF), whereas the power grip requires two DOFs [21]. In both grips, the thumb should be opposed to the fingers [22]. Also, it is acceptable to couple the movements of the index and middle finger [22]. The device should allow for some passive finger abduction/adduction of the MCP joint to accommodate slightly deformed hands and be comfortable during use. For patients with impaired wrist stabilization, the wrist should be stabilized in a functional (neutral) position.

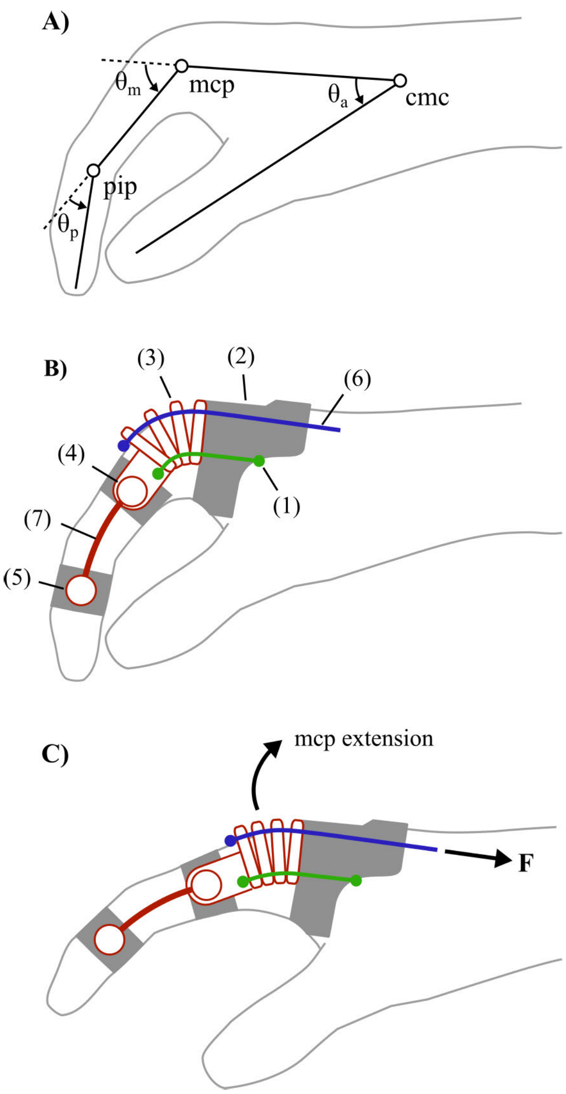

Fig. 1. A) Side view of the hand with the index finger in a flexed (closed) position, showing the metacarpophalangeal (MCP) and proximal interphalangeal (PIP) joints of the index finger, rotated by angles θ_m respectively θ_p. The thumb is rotated around the carpometacarpal (CMC) joint by an abduction angle θ_a. B) The finger extension mechanism applied to the MCP joint of the index finger consists of the following elements: (1) flexure (green) that allows for MCP joint rotation while preventing axial forces being applied to the finger, (2) hand bracket, (3) spacer segments, (4) middle segment, (5) distal segment, (6) cable (blue), (7) metal rod which length is customized during fitting such that the connectors are located halfway the proximal and middle segments of the index finger. C) Pulling on the cable with force (F) will extend the MCP joint of the index finger. The PIP joint angle is fixed.

D. Weight

The hand-mounted part of the exoskeleton should weigh less than 200g to be acceptable for use during daily activities [22].

E. Size

The height of the mechanism from the dorsal finger surface should be limited to not hinder hand function. We consider 8 mm (e.g. one-half the thickness of the finger) to be an acceptable mechanism height for ADL purposes.

F. Usability

The exoskeleton should allow for independent donning and doffing [22]. Control of the device should be easy and intuitive.

G. Adaptability

The device should be adaptable to fit various adult hand sizes [12].

III. Design

A. Finger Extension Mechanism

In Fig. 1B the key components of the finger extension mechanism are identified. The finger extension mechanism straightens a flexure (green) that is mounted next to the index finger by pulling on a cable (blue). The flexure allows for joint rotation, while preventing axial forces being applied to the finger. The axial compressive forces that result from the tendon are not transferred to the finger but to the segment-structure of the orthosis. The rotational axis of the mechanism is aligned with the rotational axis of the MCP joint. The proximal end of the flexure is secured to the hand bracket. The distal end of the flexure is secured to the most distal 3D-printed segment. This segment is then connected to a female connector, which in its turn is attached to the proximal phalanx of the index finger. Spacer segments allow for bending of the flexure, but keep the cable at a fixed distance from the flexure. Pulling on the cable results in straightening of the flexure, and thus an extension of the MCP joint. The metal rod and distal segment prevent flexion of the PIP joint. The distal segment is attached to a female connector that is secured to the middle phalanx of the index finger. The length of the metal rod can be customized during fitting to align the connectors to the proximal and middle phalanxes of the index finger. For simplicity, only the extension of the MCP joint is considered in Fig. 1B and 1C. Hyperextension of the finger joints is prevented as the segments cannot be extended further than neutral position (0° flexion). The DIP joint is left unsupported as to not impede fingertip sensation of the user. The mechanism can also be secured to the combined index and middle finger, to allow extension of both fingers simultaneously. For testing purposes, body-powered actuation was implemented.

B. Wrist and Thumb Support

A Bowden cable configuration, including a PTFE liner and 1 × 7 nylon-coated stainless steel wire (0.5 mm diameter, 18.2 kg tensile strength) removes the need for having the actuation source mounted close to the finger. This reduces the weight of the hand-mounted part. A static wrist splint (LP Support, USA), mounted on the ventral side of the arm provides an anchoring point for the Bowden cable, and keeps the wrist in a neutral position. The thumb is fixed in an opposed position using a magnetic connector and metal rod, such that the flexed index finger touches the tip of the thumb.

C. Donning Procedure

Patients with hand motor impairment often have difficulties with correctly positioning their hands and fingers to facilitate exoskeleton donning. To ease the process of donning (Fig. 2A), this procedure is split into two steps: 1) The female finger connectors are secured to the index finger (proximal and middle phalanx) and thumb (proximal phalanx) with medical adhesive tape. If a simultaneous movement of the index finger and middle finger is desired, the adhesive tape can be wrapped around the combined index and middle finger. 2) The device

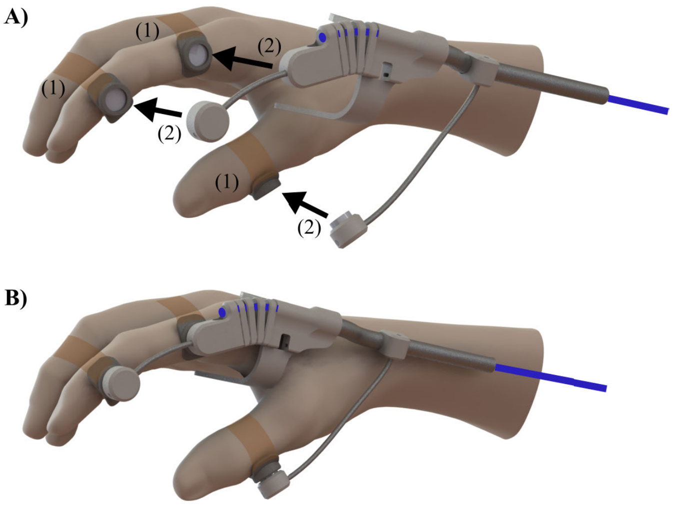

Fig. 2. A) The donning process of the exoskeleton that simultaneously extends the index and middle finger. (1) The female connectors are first secured to the finger and thumb with medical adhesive tape. (2) Then the middle and distal segments (containing magnets) are attached to the female connectors from the medial side. B) The EXTEND exoskeleton when fully donned.

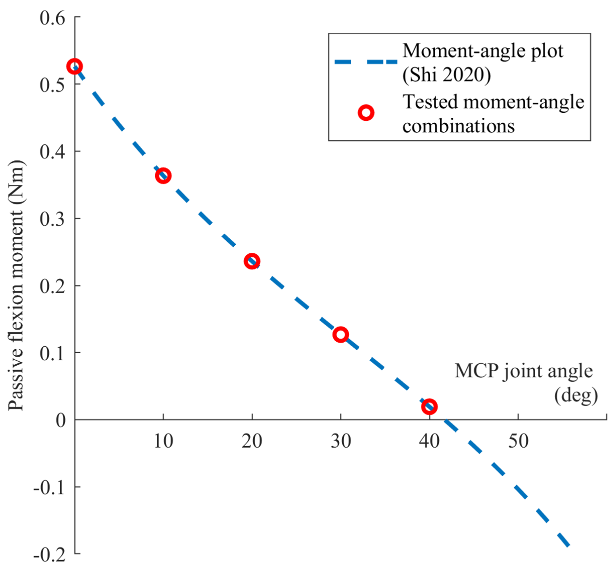

Fig. 3. Moment-angle plot of stroke patient with high finger joint stiffness (dashed blue line), derived from [19]. The performance of the extension mechanism was tested by measuring the cable actuation forces at the marked locations (red circles).

is attached to the fingers by positioning the mechanism onto the female connectors from the medial side. The neodymium magnets (8×5mm, N45 grade) that are glued to the mechanism and will attach to the metal plate of the female connector, providing a sturdy connection. The female connectors are secured halfway the proximal and middle phalanxes, such that their position matches the position of the magnets. Fig. 2B shows the device when fully donned.

IV. Technical Characterization

A. Grasp Size

The grasp size was evaluated by mounting the exoskeleton to an average-sized hand of a healthy subject.

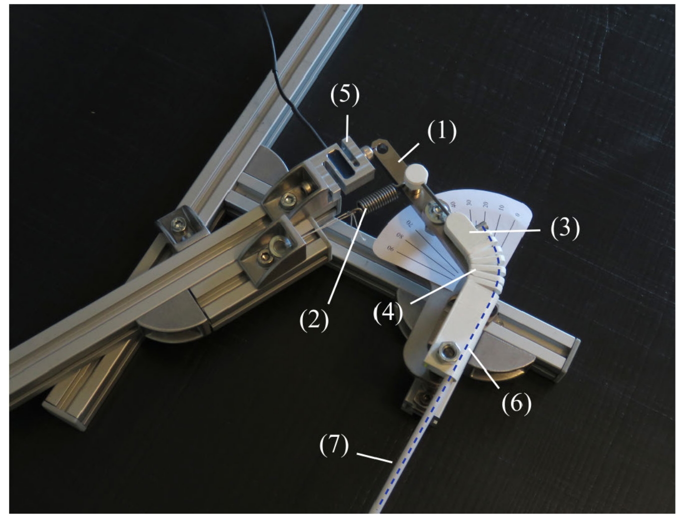

Fig. 4. Experimental apparatus consisting of a mechanical finger (1) to measure the cable actuation force required to counteract the flexion moment provided by the tensioned spring (2) with the extension mechanism (3) for different MCP joint angles. The extension mechanism is aligned with the MCP joint (4). The passive flexion force is measured by the load cell (5). The cable (6, in blue) is guided by the Bowden cable (7) to the actuation handle (not depicted). The Bowden cable was not bent during the measurement.

B. Cable Force

To characterize the performance of the finger extension mechanism, the cable activation forces were measured to extend a mechanical finger at different MCP joint angles while simulating a high joint stiffness. The cable activation force is defined as the lowest cable force that counteracts the passive flexion moment. The moment-angle relationship of a finger with a high MCP joint stiffness (k=0.63 Nm/rad) was derived from Shi et al. [19], see also Fig. 3 (dashed line). These data were used as a reference to set the passive flexion moment of the mechanical finger between 0° and 40° (resting angle) MCP flexion, see Fig. 3 (red markers).

1) Experimental Setup: The measurement device (Fig. 4) consisted of a mechanical finger with a single degree of freedom (MCP joint). A support containing a load cell is bolted onto the base, such that when the finger is flexed, the tip rests perpendicularly against the load cell. By changing the position of the support, different flexion angles of the mechanical finger can be set, according to Fig. 3. The appropriate passive flexion moment at each flexion angle, also according to Fig. 3 were generated by tensioning a helical spring such that the force measured below the tip of the mechanical finger by the load cell (KD24s, ME Messsysteme, Germany) times the moment arm (90 mm) equals the passive flexion moment from Fig. 3 at that specific joint angle. The extension mechanism was mounted onto this mechanical finger to counteract the passive flexion moment. The extension mechanism was operated by pulling on the cable that was guided through a Bowden-cable arrangement to a handle. The cable force was measured with a force sensor (Futek, USA) mounted between the cable and the handle.

2) Methods: The extension mechanism was extended by slowly pulling on the cable with a constant rate and releasing the tension on the cable with a similar constant rate. This was done at 0, 10, 20, 30 and 40° of MCP flexion. The activation

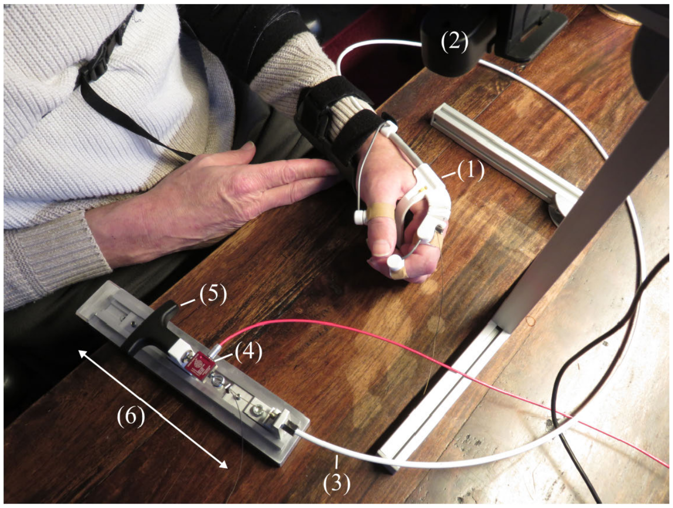

Fig. 5. Test setup used during evaluation of the kinematics and cable forces with the finger exoskeleton supporting the extension movement of the index finger. (1) EXTEND exoskeleton; (2) Webcam; (3) Bowden cable; (4) Force sensor; (5) Actuation handle; (6) Slider.

force is defined as the lowest cable force that causes the force measured below the tip of the mechanical finger to be < 0.1N. This is an indirect measure that the passive flexion moment is compensated. Each moment-angle combination was measured 3 times and the mean and standard deviation of the cable force were determined.

V. Evaluation of Patient Interaction

The exoskeleton-patient interaction was evaluated with four stroke patients that have limited finger extension capabilities. Other inclusion criteria included a normal passive finger range of motion, no excessive spasticity upon manual testing, and patients should be capable of following verbal instructions and should be 18 years or older. Additionally, participants should have the ability to perform repeated arm movements between the left and right compartments for the Box and Block test. Ethical approval for this study was obtained from the Ethics Committee of the University of Twente (ref. number 2022.129). Ethical approval from a medical ethical committee was not required, as the Medical Research Involving Human Subjects Act was not applicable. All participants gave their informed consent prior to the study onset. The goal of this evaluation was to investigate the performance of the exoskeleton when mounted to the hand of a patient.

At the start of the measurement, the mean grip strength of the impaired hand across three measurements was recorded with a hand-held dynamometer (Jamar). Also, the MAS score was determined for each subject by one rater to be able to compare MAS scores between participants.

A. Range of Motion

We measured the active range of motion (ROM) of the index finger while the subject was seated on a chair, with his elbow flexed to 90 degrees and wrist supinated. The wrist splint kept the wrist in a static position of 0° flexion. Both the PIP and DIP joint angles were approximately 20 ° for all participants. A webcam (640 × 480px, 20 frames/second) was placed perpendicular to the sagittal plane of the hand, aligned with the flexion-extension axis of the MCP joint, at a distance of approximately 20 cm. Participants were required to immediately inform the researcher when adverse events such as discomfort or pain occurred such that the test could be immediately stopped. After each session, the researcher inspected the hand of the participant for pressure marks, redness or other signs of physical discomfort.

1) Without Exoskeleton: To measure the active range of motion without exoskeleton, the subject voluntarily extend his index finger from the resting position to a maximum extended position, while the finger movements were recorded with the camera. Lines were drawn manually onto stills of the captured video with a custom Matlab script (Matlab 2021b, Mathworks, USA), to estimate the index finger MCP and PIP joint angles in rest and in during maximum finger extension.

2) With Exoskeleton: The extension mechanism was mounted to the affected hand of the subject, to support extension of the index finger MCP joint. The subject was then asked to operate the extension mechanism by pulling on the cable with his unaffected hand to extend the index finger from a resting position to a maximum comfortable extended position and back to the resting position, at a slow, constant speed. The participants were instructed to relax their affected hand during the passive extension movements with the mechanism. These movements were repeated three times. Then, the same procedure was performed, but now with the extension mechanism connected to the combined index and middle finger. During each trial, video recordings of the finger movements were made from which the kinematics were determined, similar as was done for measurements without exoskeleton. Additionally, the cable forces required to extend the finger(s) were recorded with a force sensor (Futek, USA) that was mounted between the operating handle and the cable. See also Fig. 5 for an overview of the test setup.

3) Box & Block Test: The Box & Block Test is a functional test to measure gross manual dexterity [23]. The test consists of a rectangular box with two compartments that are separated by a partition and contains 150 colored wooden blocks (2.5cm in size) that should be grasped and transferred. Subjects were instructed to move as many blocks as possible in 60 seconds from one compartment to the other, (1) with their unsupported affected hand, and (2) with their affected hand supported by the exoskeleton that was operated by their unaffected hand. For each tested condition the number of transferred blocks in 60 seconds were counted.

VI. Results

The developed exoskeleton is shown in Fig. 6 during maximum MCP joint flexion (A) and maximum MCP joint extension (B). The PIP joint is fixed. The hand-mounted part of the exoskeleton weighs 87 g., including a size S wrist splint (43 g.), or 105 g. including a size M wrist splint (61 g.). The form-factor of the device is small as the exoskeleton extends only 6 mm above the dorsal surface of the hand. The height of the cable above the flexure determines the extension moment that is created by the mechanism for a given cable force. In the prototype the height was fixed at 12.5 mm. To operate the mechanism in this configuration from a fully closed ($\theta_{mcp} = 90°$) to a fully extended ($\theta_{mcp} = 0°$) position, a cable excursion of 20 mm is required. The design is also modular: by removing or adding flexible segments, the

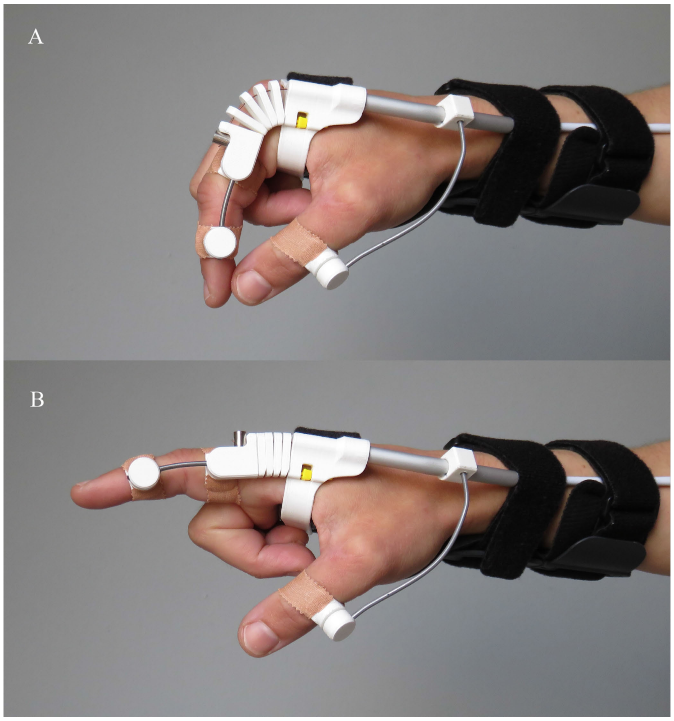

Fig. 6. A) Prototype of the finger exoskeleton mounted to the hand of a healthy user, with the MCP joint in maximum flexion. B) Prototype of the exoskeleton, with MCP joint in maximum extension. Grasping an object with a diameter of 7 cm is possible with the device in combination with an average-sized hand.

TABLE II
MEAN CABLE ACTIVATION FORCES FOR EACH TESTED MOMENT-ANGLE COMBINATION WHILE SIMULATING A PARETIC FINGER WITH A HIGH FINGER JOINT STIFFNESS

MCP joint angle (deg)	Passive flexion moment (Nm)	Cable activation force (mean ± std) (N)
0	0.53	58.8 ± 1.24
10	0.36	38.5 ± 0.78
20	0.24	24.2 ± 0.44
30	0.13	12.0 ± 0.40
40	0.02	2.5 ± 0.13

std: standard deviation

device can be easily adjusted to different hand dimensions. Because the flexure can bend anywhere along the line of flexible segments, no perfect alignment with the MCP (or PIP) joint is required.

A. Cable Force

The mean cable activation forces were determined for each of the MCP moment-angle combinations marked in Fig. 3. The results are shown in Table II. As an example, the measured cable and finger tip forces measured during three extension movements are shown in Fig. 7 while a passive moment of 0.53 Nm was set with the spring at 0° MCP flexion.

B. Evaluation of Patient Interaction

The characteristics of the four stroke patients who participated in this evaluation study are listed in Table III. S1 had no

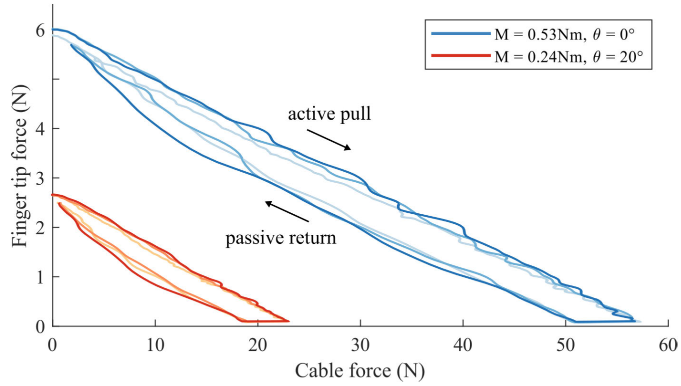

Fig. 7. The extension mechanism was extended by slowly pulling on the cable with a constant rate and releasing the tension on the cable with a similar constant rate. The graph shows the cable forces and forces measured at the tip of the mechanical finger, while counteracting a passive flexion moment of 0.53 Nm of the mechanical finger at 0° MCP flexion (blue) and while counteracting a passive flexion moment of 0.24 Nm at 20° MCP flexion (red). Per condition, three trials are shown (different shades of red and blue). The direction of active pull on the cable and passive return of the mechanical finger to the resting position are indicated with arrows.

voluntary muscle activation of the flexor and extensor muscles. For S3 we used no thumb support as his thumb was already in an opposed positioned. S2 and S4 struggled to relax their finger flexors which led to highly variable muscle tone. For S4, we therefore decided to stabilize the DIP joint with an additional metal rod secured to the index finger with adhesive tape, as excessive flexion caused the DIP to render the index finger dysfunctional. For S2 we decided to attach the distal portion of the extension mechanism to the distal segment of the index finger. Due to the excessive tone of the thumb flexor muscles, we required a stiffer thumb rod for this participant to keep his thumb in an opposed position.

1) Range of Motion: The MCP and PIP joint angles of the index finger in resting and maximum extended position are listed in Table IV. For three subjects (S1, S2 and S4) no active joint extension was measured. For S3, the MCP range of motion was 12°, and the PIP range of motion was 14°.

In Table V the MCP joint resting angles and maximum extension angles are listed when the subject extended his finger with the extension mechanism to a maximum position by pulling on the actuation handle. The required cable forces to extend the finger to achieve this position are also listed in this table. Subjects with the highest MAS scores, required the highest cable forces to extend their index finger. Also, higher forces were required to extend the index and middle finger simultaneously, than to extend the index finger alone. By comparing the maximum extension angles of Tables IV and V it can be seen that the extension mechanism improved the finger extension. On average the extension angle increased with 46° (range 7 to 73) were achieved across all participants. For S1 and S4 the exoskeleton had a large effect on the MCP joint resting angle of the index finger.

2) Box & Block Test: Subjects should have sufficient proximal (arm) control to position their hand from one compartment to the other to complete the Box & Block Test. Only two of the four subjects (S2 and S4) were able to accomplish this. Therefore, the results from the test were only reported in Table VI for these subjects. From our data it is observed that both subjects were able to successfully transfer several

TABLE III
SUBJECT CHARACTERISTICS

ID	Gender	Age (y)	Weight (kg)	Dominant hand	Affected hand	Time since complaints (y)	Grip strength impaired hand (kg)	MAS score (0-4)
S1	M	61	80	Right	Left	1	0	3
S2	M	27	66	Right	Right	15	9.5	3
S3	M	76	85	Right	Left	5	4.2	3
S4	F	19	60	Right	Right	4	10.5	2+

ID: subject ID; F: female; M: male;

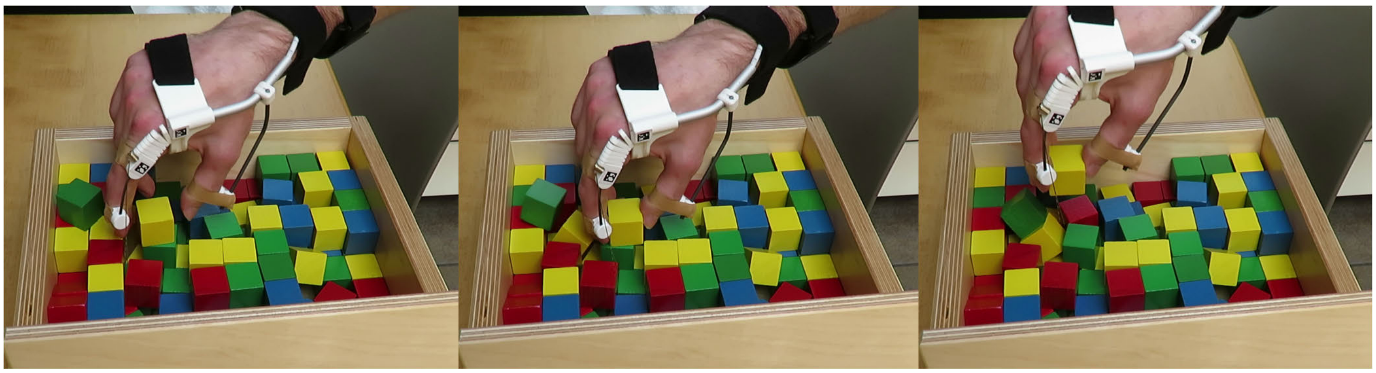

Fig. 8. Stills from the Box & Block Test of P02 showing the initial hand opening (left), actual grasping (middle) and lifting (right) of one block.

TABLE IV
INDEX FINGER RESTING AND MAXIMUM ACTIVE EXTENSION ANGLES

ID	$\theta_{mcp,r}$ (°)	$\theta_{pip,r}$ (°)	$\theta_{mcp,e}$ (°)	$\theta_{pip,e}$ (°)
S1	55	75	$(55)^{\dagger}$	$(75)^{\dagger}$
S2	53	32	$(53)^{\dagger}$	$(32)^{\dagger}$
S3	59	35	47	21
S4	74	96	$(74)^{\dagger}$	$(96)^{\dagger}$

ID: subject ID; †: no active joint extension was measured; $\theta_{mcp,r}$: index finger MCP joint resting angle; $\theta_{pip,r}$: index finger PIP joint resting angle; $\theta_{mcp,e}$: index finger MCP joint maximum active extension angle; $\theta_{pip,e}$: index finger PIP joint maximum active extension angle;

blocks with the exoskeleton mounted to their hand, compared to none without exoskeleton. In Fig. 8 three stills of the Box and Block Test of P02 are shown during grasping of one block.

VII. DISCUSSION

In this study we presented the mechanical design and evaluation of a novel exoskeleton that supports the finger extension of stroke patients. A technical evaluation of the device showed that the mechanical structure was able to counteract the passive flexion moments corresponding to the index finger of a severely affected stroke patient (with an MCP joint stiffness of k = 0.63Nm/rad). The maximum cable activation force that was measured during this evaluation was 58.8N. The device can achieve the desired grasp size of 7 cm when mounted to an average-sized hand of a healthy user. The device was also able to improve the extension of the index finger of four stroke patients when performing extension movements with the exoskeleton mounted to their hand. In a functional test (Box & Block Test) with two stroke patients, we demonstrated that the EXTEND exoskeleton improved their ability to pick up 2.5 cm wooden blocks.

In Table VII we present a brief comparison of the characteristics of our developed device with other devices found

TABLE V
MEAN MCP JOINT ANGLE ($\theta_{mcp,e}$) AND CABLE FORCE (F_c) AT MAXIMUM EXTENSION WITH THE EXOSKELETON ATTACHED TO THE INDEX FINGER (DIGIT I), OR COMBINED INDEX AND MIDDLE FINGER (DIGITS I+II)

ID	Digit	$\theta_{mcp,r}$ (°) mean (range)	$\theta_{mcp,e}$ (°) mean (range)	F_c (N) mean (range)
S1	II	31 (31 - 33)	5 (2 - 6)	37.8 (32.9 - 43.2)
	II + III	37 (34 - 42)	3 (2 - 4)	39.7 (36.5 - 44.6)
S2	II	45 (39 - 51)	9 (8 - 9)	34.4 (31.6 - 37.3)
	II + III	$54^{\dagger}$	$7^{\dagger}$	$56.0^{\dagger}$
S3	II	52 (46 - 63)	40 (35 - 43)	40.9 (37.7 - 47.4)
	II + III	42 (36 - 50)	23 (19 - 25)	62.5 (52.8 - 71.7)
S4	II	32 (32 - 33)	1 (1 - 2)	20.4 (19.0 - 21.8)
	II + III	27 (26 - 28)	5 (4 - 7)	35.1 (32.6 - 37.6)

ID: subject ID; $\theta_{mcp,e}$: index finger MCP joint maximum extension angle; II: index finger; III: middle finger; †: based on one trial

TABLE VI
SCORES OF THE BOX % BLOCK TEST, DENOTING THE NUMBER OF BLOCKS TRANSFERRED BY THE AFFECTED HAND IN 60 SEC

ID	Without exo (# of blocks)	With exo (# of blocks)
S2	0	6
S4	0	5

TABLE VII
COMPARISON OF THE MAIN ASPECTS OF THE EXTEND EXOSKELETON WITH THE STATE OF THE ART

Aspect	EXTEND	HERO Grip Glove [8]	SaeboFlex [13]	SaeboGlove (Saebo, USA)	HandSOME [14]
Design Type [12]	Compliant	Compliant (glove)	Base-to-distal	Compliant (glove)	Matched axis
Actuation strategy	N/A	Active (pneumatic)	Passive (ext. springs)	Passive (rubber bands)	Passive (bungee cords)
Weight (g)	105	284	1587	453	220
Extension moment (Nm)	0.53	N/A (80N tensile force)	N/A	N/A	4
Min. grasp size (cm)	0	0	6-7*	3-4*	0
Max. grasp size (cm)	>7	>7†	>7†	>7†	>7†
Dimensions (cm)	24x9x5	33x10	34x23x34	23x20x7	N/A
Active DOF (digits I-V)	II, or II+III	I to V	I to V	I to V	I-V
Wrist support (Yes/No)	Yes	Yes	Yes	Yes	Yes
Fingertip covered (Yes/No)	No	Yes	Yes	Yes	No

N/A: not available; †: estimation; *: estimation, but highly depending on user's grip strength and impairment level.

in literature. Compared to the state of art, our exoskeleton is lightweight, has a small volume and is easily mounted to the affected hand.

Several limitations regarding the design and test methods are addressed below.

In our device, the magnets that attach the extension mechanism to the finger connectors are subjected to forces parallel to the surface, which lowers the adhesive force to approximately 15-25% of their specified adhesive force. A raised brim on the edge of the finger connectors counteracts this effect partially. Still, the adhesive force is a limiting factor of the maximum force that can be applied to the finger. Additionally, the tape and magnets were chosen to facilitate easy donning and doffing once attached, but securing the female connectors with medical adhesive tape to the finger might not be a feasible solution for long-term use. In the future we will therefore consider using a different connector design and attachment location.

In this study we focused on the technical aspects of the mechanical design. In a future study we will focus more on usability aspects such as comfort during prolonged daily use during, and independent donning and doffing, durability and robustness of the mechanism (e.g. of the cable and flexure). User questionnaires such as D-QUEST could be a feasible option to obtain results about user satisfaction with an assistive device [24]. Assessments such as the Jebsen Taylor Hand Function Test [25] or Wolf Motor Function Test [26] could be performed with and without device to test the functional capabilities of the device.

To be able to evaluate usability aspects, a portable actuation strategy should be implemented, such as body-powered actuation, or joint stiffness compensation based on a negative spring mechanism. Both strategies have the potential to be easy and simple to use, while they don't require complex, expensive and heavy components which are typically involved in electrically or hydraulically powered systems. Body movements directly control the hand opening as the cable of the extension. Body-powered actuation is commonly applied in upper extremity prosthetics [27], where often contralateral shoulder movements control the prosthesis. In stroke patients using the contralateral side of the body may pose problems as it can lead to overstraining of the non-affected side. The application of body-powered control strategies should therefore be investigated further. Another actuation strategy is to use extension springs in a particular (so-called negative stiffness) configuration to compensate for the intrinsic stiffness of the finger joints [28]. Ideally, the passive flexion moment at each joint angle is perfectly counteracted by the energy stored in a normal extension spring. For the user to operate the device now only small voluntary finger flexion forces are required. A downside of this strategy is that it cannot compensate for hysteresis in the system.

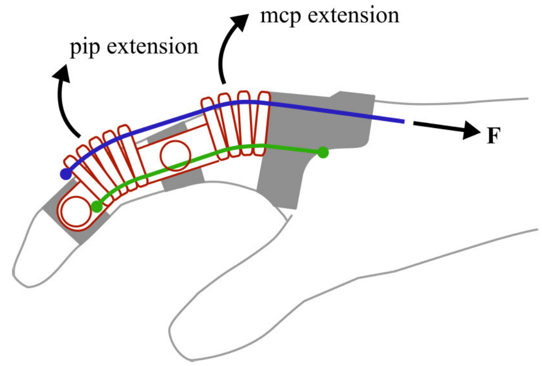

Fig. 9. The finger extension concept of Fig. 1 extended to the PIP joint. Pulling on the cable (in blue) with force F results in a simultaneous extension of both the PIP and MCP joint.

The developed finger extension mechanism can be easily extended to the PIP joint, such that simultaneous control of the MCP and PIP joint is possible, see also Fig. 9. We observed promising results of extending the finger with only active MCP control. Future work should also explore the finger kinematics of the finger when assisting both MCP and PIP extension. Additionally, we will assess the added benefit of actuation the combined index and middle finger, for example during functional tasks, or the Box and Block test.

Improvements to the design to allow actuation of multiple digits simultaneously, may include lowering the cable forces, either by improving the Bowden cable transmission efficiency, or increasing the moment arm between the flexure and cable.

The efficiency of Bowden cable transmissions largely depends on the geometric configuration of the system [29].

When evaluating the exoskeleton with users, the cable of the extension mechanism was attached to an operating handle through a Bowden cable. Even though the radius of curvature of the Bowden cable experimental setup was large (>30 cm), the frictional losses due to a wrap angle of 360° caused the force transmission to be less efficient. The cable activation forces will be lower if the wrap angle is decreased, e.g. when the cable is directed from the hand towards the actuation system in a straight line.

Increasing the height of the cable above the flexure can further decrease the required activation force, but will also increase the size of the mechanism.

In this design we secured the finger connectors to the proximal and middle phalanx of the finger, while the distal phalanx was left unsupported to not impede fingertip sensation. As the finger flexor tendon crosses multiple joints, the DIP joint will typically flex when extending the fingers. Therefore, in a future design, we might reconsider fixing the DIP joint to 15° flexion, as suggested by [21].

Also it will be worth investigating the possibilities of adding flexion assistance, especially for patients with limited grasp strength, by replacing the cable with a flexure.

In this present study, participants with excessive spastic (velocity-dependent) reflexes of the fingers during passive extension were excluded from participation. In future research it may be interesting to also measure EMG to quantify the contributions of muscle activity and soft tissue to resistance during passive finger movements.

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